FAST COMPENSATION OF FLICKER AND REACTIVE POWER IN ARC FURNACE SYSTEMS WITH CONTROLLED CURRENT SOURCES

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By

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Certificate

It is to certify that the work contained in the thesis entitled ***"Fast compensation of flicker and reactive power in arc furnace systems by controlled current sources"*** by Vishvajit has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

(April, 2000)

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I take great pleasure and satisfaction, in dedicating this work to Kuljeet, who has been a rigid moral support and the urge to achieve this goal.

Acknowledgment

I would like to express my deepest gratitude to my supervisor *Prof. A. Joshi,* to whom I owe more than I can possibly express, for his warm guidance and father like gesture that gave me the moral strength and determination for the completion of this work.

I also take this opportunity to express my deepest gratitude to *my parents* and *my sisters* for their invaluable support and affection throughout the duration of this work.

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Last but not least, I would like to thank my friends Satya Prakash and Shobhit Gupta for the warm affection and help they showed whenever I had some problem, making my stay at IIT Kanpur a memorable one.

Vishvajit

I.I.T, Kanpur

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CONTENTS

Abstract

Arc furnaces are probably one of the worst kinds of load on the power system. Arc behavior is often very random, giving rise to large amount of harmonics and a poor voltage profile at the Point of common coupling. Besides this, the system also suffers from flickering of incandescent lamps at loads connected on the same bus. To overcome these problems an arc model has been structured so as to simulate an arc furnace installation. The system is compensated with S.V.C as well as controlled current sources. The results indicate that the current compensation scheme studied in this thesis gives considerably better results than the conventional compensation approach using S.V.C's. The level of flicker has been reduced to a great extent (80-85%) , indicating the effectiveness of the scheme for fast compensation of flicker and reactive power.

Chapter 1

INTRODUCTION

1.1 History of electric arc furnace steelmaking

Formulations of steel and other metals have been known since Biblical times. When Tubal Cain scraped ashes from his fire and discovered that he had reduced Iron or smelted metal, it is probable that his first thought was to make a weapon of destruction.

The electric furnace was invented by a Frenchman, Pichon for which he was granted a patent on March 16, 1853, for his claim of economically melting minerals and metals. The development of dynamo in 1867 made the electric furnace feasible [11].

The first practical application of using electric power for melting steel was by Sir William Siemens in 1879. He used a crucible with horizontal electrodes to form a single phase arc above the crucible. This principle is still in use despite its being inefficient and

costly. Stassano, in Italy suggested an indirect arc. Rennerfelt proposed a design that consisted of, two inclined electrodes and a third vertical electrode so as to direct the arc towards the bath for increased efficiency [11].

The next step in the development involved direct arc furnaces. These designs were characterized by vertical electrodes and current travel from the electrodes to the bath . The main improvement was that the heat generated by the arc was held within the scrap during melting which tended to reduce erosion.

The first electric furnaces were usually small units of 1 to 15 tons. By 1930, production had increased to annual output of 686,111 net tons [11]. As new alloys were developed for tool, valve, and stainless steel applications the industry continued to expand. At the start of World War II, the technology had improved to the point where the electric furnace industry was ready to provide the new types and greater quantities of metal required for military purposes.

1.2 Problems associated with arc furnace operation

During melting down of the cold charge within the furnace, the three phases act much like three single phases. Two electrodes can strike the charge and draw the current without any current flowing through the third electrode. Currents of varying magnitude flow in the whole system (including the supply system). These currents are limited only by the impedance of the arcs, which is essentially resistive, the impedance of the secondary circuit, which is partly resistive and mostly reactive, the impedance of the transformer and by the impedance of the supply system.

It is during the early part of the meltdown when these fluctuating currents cause the greatest disturbance in the supply system. If not properly controlled they will cause objectionable flickering of lights that uses energy from the same power supply system [2].

As the heat in the furnace progresses, conditions improve. When the refining stage is reached, the molten steel is covered with a hot slag yielding conductive vapors that help to stabilize the arc current and the load on the supply system.

Empirical data collected by the utilities show a great variance in single-phase load swings among furnaces [7]. Abrupt changes in the circuit impedance cause these load swings. The impedance of the arc part of the circuit will vary for a number of reasons such as those listed below,

1. The metal in the furnace may melt away from the electrode or it may be forced away from the electrode by the inductive effect of the arc current, thus abruptly increasing the impedance of the arc.
2. The electrode oxidizes away and ionizes. This increases the arc impedance slowly.
3. The physical and chemical make-up of one charge is different from the next. This is known to have a great effect upon the behavior of the arc.
4. The arrangement of the charge materials in the furnace has an effect upon the behavior of the arc.
5. The relative amount of air blown upon the arc and its moisture content will have a greater or lesser chilling effect to increase or decrease the impedance of the arc.

Thus it can easily be seen that electric arc furnace is a large and potentially severe load on the electrical supply network. Owing to the nature of the electric arc phenomena, and depending on the supply capacity, the size of the furnace and the mode of furnace operation, the arc furnace can result in serious levels of electrical disturbance on the network. Estimation and control of the disturbances is very much a system problem, and at the design stage of a new installation, input from the electric utility, the furnace manufacturer and the plant engineering staff will be required, if the level of disturbances is to be kept within limits.

1.3 Methods of arc furnace compensation

Conventionally capacitors were used in the electrical system that acts analogous to an accumulator in a hydraulic system. They will draw and store the excess energy from the system whenever the force producing the energy exceeds normal and return this energy to the system whenever the force falls below normal. Thus capacitors are a means used to help stabilize the voltage and current in line.

A synchronous condenser may be designed to run on active or reactive energy from the line and produce active or reactive energy in the form of mechanical energy or electrical energy. The mechanical energy may be drawn off the shaft of the rotating machine by the attachment of a gear. The electrical energy, as active watt-hours or reactive var-hours is fed back into the line.

The arc furnace is a highly reactive load because of the inherent and very often added reactance in the circuit to stabilize the arc. The arc furnace draws energy from the line, converts only a part of it into useful heat, and the rest is fed back into the line as reactive energy. It does no good to the line, and a synchronous condenser is used to convert it back to useful energy again. By converting the reactive energy to active energy again, the synchronous condenser converts a low power factor load to a high power factor on the line and its flywheel effect absorbs fluctuations in the line voltage and current caused by the arc furnace.

However in recent years, static VAR compensators using thyristors have been built which are fast superseding the conventional methods for arc furnace compensation because of their being superior in respect of response, maintenance and efficiency [7]. They can compensate for the fundamental reactive as well as, to a limited extent, the harmonic content in the supply current.

1.4 Problem formulation

It is seen that an arc furnace behaves quite randomly in the sense that the arc impedance changes abruptly. The real and reactive powers drawn by the furnace also fluctuate randomly and often severely thus putting considerable stress on the system. This leads to a poor voltage profile at the bus supplying the arc furnace installation and also creates flickering of incandescent lamps and other disturbances to the other loads being supplied from the same bus.

To overcome these problems, different compensating schemes have been employed, the one that is being used at most of the installations is compensating with the help of S.V.C's . Although they are far better than the synchronous condensers that were conventionally used but still they are not able to compensate for the problem of flicker to reasonable extent, as will be shown in the following chapters .

The objectives of this study are,

- Formulate an appropriate model for an arc so as to simulate a furnace installation.

- Evaluate the performance of the arc furnace,
  1. Without any compensation.
  2. With presently used S.V.C scheme.

- Investigate the affects of compensating the arc furnace instantaneously with the help of a controlled current source on the reduction of flicker and other problems.

1.5 Thesis outline

This study has been performed keeping the fore mentioned objectives in mind. The entire study revolves around how to simulate an arc furnace and then compensate for the flicker and other problems.

The thesis is organized as follows,

Chapter 2 deals with different models of the arc and the one that has been structured so as to cover different aspects of arc furnace operation used for the purpose of this study. This chapter also gives the benefits of the proposed model as compared to the conventionally used models of an arc.

Chapter 3 gives an idea of the kind of load an arc furnace is, looking from the source point of view. An arc furnace installation has been simulated and the behavior of the arc has been studied. The chapter gives an idea of the kind of harmonics generated and the reactive power required by the arc furnace. Flicker has also been defined and evaluated for the bus supplying the furnace installation.

Chapter 4 discusses the performance of the furnace installation with a S.V.C connected in parallel for the compensation of reactive power. It is shown that although we have a reduction in the average reactive power required by the furnace but still the harmonics in the source current are not suppressed to the required extent. What is most important is the level of flicker after compensation. It is shown that we do not have appreciable reduction in the level of flicker at the critical bus (the one supplying the furnace).

Chapter 5 revolves around the theory of instantaneous compensation proposed by Lai [10] and the modification carried out to take care of the harmonic powers as well. The method used to evaluate the reference current for compensation takes into account the

fundamental as well harmonic powers drawn by the load thus giving far better results for rapidly varying loads such as arc furnaces.

Chapter 6 investigates the effects of compensating an arc furnace with the help of, first an ideal current source and then with a current source realized by a 2level, 3phase voltage source inverter. It is shown that by using the scheme developed in chapter 5 and an ideal current source we can in fact improve the performance of the furnace excellently. We'll see that the harmonics in the source current are reduced drastically and the level of flicker comes down by as much as 80-85%. Although the performance deteriorates slightly when compensating with a 2level inverter but still the results are far better than those obtained with S.V.C.

On an overall the study brings out the fantastic improvement in the performance of arc furnaces, if compensated instantaneously with voltage source inverters as compared to the presently used compensation schemes using S.V.C's.. As concluded in chapter 7, we can see that still there is scope for improvement upon the results obtained in this study and some of the possible alternatives have been listed as the scope for future work.

Chapter 2

MODELLING OF AN ARC

2.1 Introduction

One of the major difficulties in simulating an arc furnace installation is the availability of a proper and concise model of an arc. Although arc has been studied to a great extent but still a satisfactory model is lacking basically because of a highly non-linear relationship between the arc voltage and current and also due to the unpredictable behavior of the arc current during the initial period of the melt.

Though we have in literature [9] quite a few models of arc but their main drawbacks are that either they are valid for relatively small current area (Circuit breakers, Welding equipment) or they involve thermodynamics to a great extent thus requiring elaborate knowledge of thermodynamics and material science.

We present here three models of an arc that does not require much background of thermal physics.

1. Electro Magnetic Transient Program model.
2. Arc current simulation model.
3. Variable resistance model.

2.2 Electro Magnetic Transient Program Model

A complete three phase model can be implemented using E.M.T.P [14]. The model of an arc is given by a modified version of the Mayr equation, the Cassie-Mayr formula

$$\frac{d}{dt}(Rarc) = \frac{Rarc}{\theta}\left\{1 - \frac{V^2 arc}{V^2 o}\right\}$$

where,

- Rarc is the arc resistance.
- θ is the arc time constant.
- Vo is the arc static voltage depending upon the arc length.
- Varc is the arc voltage.

Such an implementation can be done using E.M.T.P. Transient analysis of control systems module and the use of controlled voltage or current sources.

2.3 Arc Current Simulation Model

One way to simulate an arc furnace is to model its current waveshape [3]. A number of studies and measurements have been carried out into the arc furnace parameters and their

harmonic spectrum based on which a computer model for an arc current can be constructed. A typical arc current model with predefined magnitudes of different harmonics and a random variation about the same has been given below.

$$V_{arc}(t) = \sin(wt) \text{ p.u}$$

$$I_{arc}(t) = I_a(t) + I_r(t) \text{ p.u}$$

$$I_a(t) = (0.5 X_1 + 0.75) \sin(wt) \text{ p.u}$$

$$\begin{aligned} I_r(t) = & -(X_2 + 0.5)\cos(wt) + (X_2 - 0.5) \\ & + 0.22\{(X_3 - 0.5)\sin(2wt) + (X_4 - 0.5)\cos(2wt)\} \\ & + 0.26\{(X_5 - 0.5)\sin(3wt) + (X_6 - 0.5)\cos(3wt)\} \\ & + 0.10\{(X_7 - 0.5)\sin(4wt) + (X_8 - 0.5)\cos(4wt)\} \\ & + 0.22\{(X_9 - 0.5)\sin(5wt) + (X_{10} - 0.5)\cos(5wt)\} \\ & + 0.04\{(X_{11} - 0.5)\sin(6wt) + (X_{12} - 0.5)\cos(6wt)\} \\ & + 0.12\{(X_{13} - 0.5)\sin(7wt) + (X_{14} - 0.5)\cos(7wt)\} \\ & + 0.04\{(X_{15} - 0.5)\sin(9wt) + (X_{16} - 0.5)\cos(9wt)\} \text{ p.u.} \end{aligned}$$

where,

V_{arc} is the arc voltage.

I_{arc} is the arc current.

X_1 -- X_{16} are random numbers distributed uniformly between 0 and 1.

2.4 Variable Resistance Model

It has been shown in literature [11] that an arc essentially consists of a fixed reactance in series with a variable resistance. Hence we can also model an arc if we can vary a resistance randomly about a mean operating point in such a way that an arc current can be simulated.

Arc current is generally seen to have large fluctuations particularly during the initial period of the melt. Hence we simulate the arc by switching in and out different fixed resistances about a mean value and further randomly select the time period of their being in the circuit in such a way so as to best simulate the actual arc current and its harmonics.

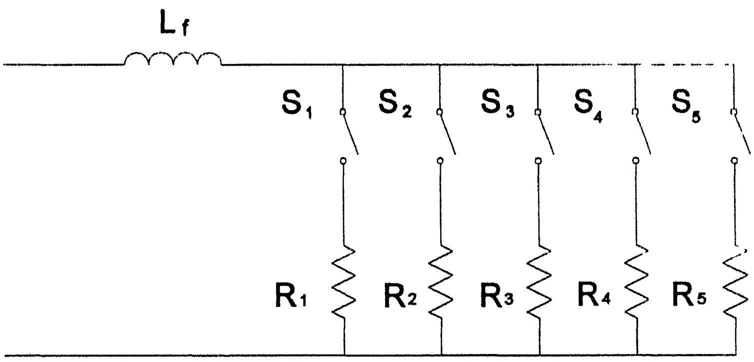


Figure 2.1 : Arc furnace model

Above figure shows how a combination of resistors and switches can be connected to simulate an arc furnace. Only one switch is on at a time and that switch is selected randomly

Table 2.1 shows the values of resistors used for simulating the arc, the switch positions and the no. of time steps for which that state will remain before another resistor is selected .

	S1	S2	S3	S4	S5	Rarc	Time
R1 = 3	ON	OFF	OFF	OFF	OFF	3	X*100
R2 = 8	OFF	ON	OFF	OFF	OFF	8	X*300
R3 = 10	OFF	OFF	ON	OFF	OFF	10	X*200
R4 = 15	OFF	OFF	OFF	ON	OFF	15	X*100
R5 = 20	OFF	OFF	OFF	OFF	ON	20	X*50

Table 2.1

In the above table ' X ', denotes a random number uniformly distributed between 0 and 1 .

This method has following advantages over others and hence is being used for the purpose of simulating arc.

- There is enough unpredictability in the value of the arc resistance to come in the following time as well as the duration for which it will remain thus simulating to a great extent the dynamic behavior of the arc .
- The arc current spectrum can be designed so as to match that of an actual arc furnace by appropriate weightages given to different resistance values.
- The power drawn by the arc can be varied by having a different set of resistance values .
- We have time intervals during which the arc has a negative resistance characteristic due to sudden variation in the resistance of the arc thus simulating the actual behavior of an arc.

Chapter 3

ARC FURNACE AS A LOAD ON THE UTILITY

3.1 Introduction

An electric arc furnace, as such, is one of the most troublesome loads to be supplied by the utilities, but looking from commercial point of view they are large revenue generators and hence form important loads for the utility. The basic problem with the arc furnace is the randomness associated with the arc impedance owing to which the arc current tends to fluctuate considerably from cycle to cycle. The only check to these rapid fluctuations is the reactance put in series with the arc, thus limiting the rate of change of current and also limiting the short circuit currents which is a common incident during the early phases of the melt [11]. The reactance forms an essential part of the system but on the other hand consumes large amounts of reactive power thus putting considerable stress on the system and limiting the real power flow to the arc furnace.

Arc furnace installations generally have large transformers that have high leakage inductance. As the arc draws large and fluctuating currents the voltage profile at the bus feeding the arc furnace deteriorates and the voltage fluctuates giving rise to the phenomena of flicker which is defined in the next section.

This chapter highlights various problems and the phenomena of flicker associated with the arc furnace if operated without any preventive and curative methods. The variations of different parameters such as, current, real and reactive power, voltage fluctuations and their harmonic spectrum are also studied.

3.2 Flicker

Flicker is defined as the low frequency (0.1 Hz to 20 Hz) modulation of the supply network voltage. The modulation results in characteristic flickering of incandescent lamps which can be most annoying when the flicker is in the 1 to 10 Hz range. Very small variations are enough to induce lightning disturbances unbearable to the human eye. For a standard 60W lamp, the disturbance becomes perceptible for a voltage variation frequency of 10Hz and relative magnitude of 0.3%.

Whenever an arc furnace is connected to a supply having a reasonable short circuit level, a proper assessment of the resulting flicker level is probably the most important aspect of the disturbance question to be addressed.

A common indicator of the level of flicker is obtained on a scale called ΔV_{10} [3], which is generally used in Japan. ΔV_{10} is the rms value of the voltage fluctuations weighed by the frequency characteristic of the human eye's sensitivity for flicker and is calculated by the following equation.

$$\Delta V_{10} = \left\{ \sum_{n=1}^{\infty} (a_n . \Delta V_n)^2 \right\}^{1/2} \qquad 3.1$$

where , ΔV_n : The frequency component at frequency f_n of the voltage .

a_n : Flicker sensitivity coefficient at frequency f_n of the human eyes as given in [4].

3.3 Arc furnace system outline

The single line diagram of the system consisting of the step down transformer the arc furnace transformer and the arc furnace is as shown in figure 3.1.

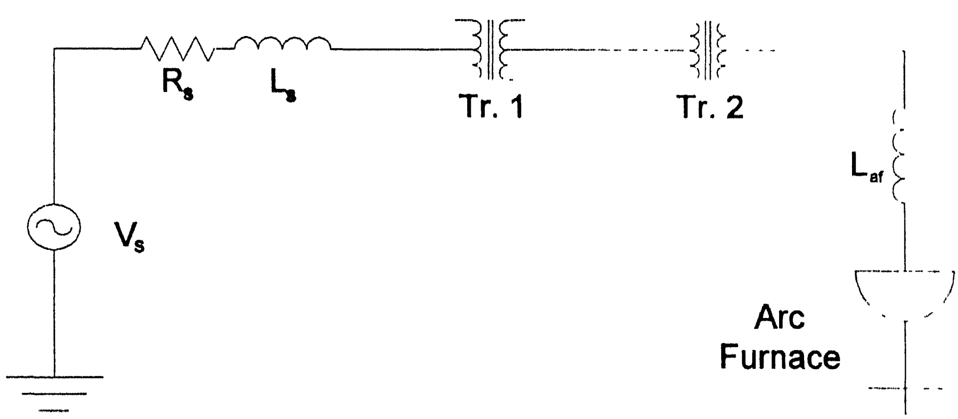


Figure 3.1 : Single phase equivalent of the arc furnace installation

Here ,

Vs = 154 kV , 3phase , 60Hz

Rs = 0.254 Ω , Ls = 58.1 μH (System Impedance) .

Tr1=154kV / 33kV , 91MVA , X = 13 % . (Step Down Transformer) .

Tr2= 33kV / 812V , 75MVA , X = 7.5 % (Arc Furnace Transformer) .

Laf= 30 mH (Current Limiting Reactor) .

The 33kV bus between the step down transformer and the furnace transformer is being considered as the critical bus whose voltage fluctuations causes flicker at other installations on the same bus

3.4 Single phase model and system equations

Due to the randomness associated with the arc the arc furnace essentially behaves as three single phase loads particularly during the early phases of the melt, hence it can be said that all the phases are relatively independent of each other. The single phase equivalent of the system is shown in figure 3.2.

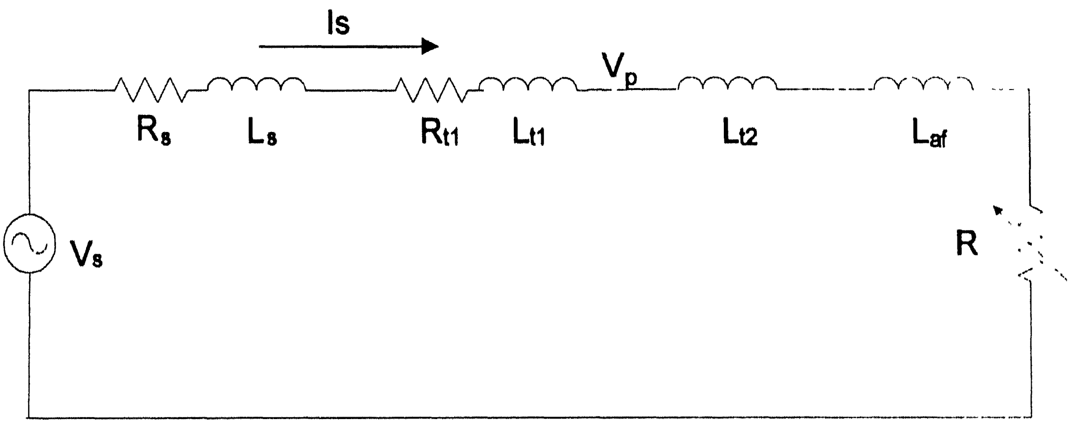


Figure 3.2 : Single phase equivalent of the arc furnace system

The values of all the parameters can be obtained from the data on the last page. The value of L_{af} is chosen such that the short circuit current is limited to around 3 kA. The value of R is variable and varies between 3 to 20 ohms in a fashion described in the previous chapter.

The differential equations governing the system are given by,

$$V_s = (R_s + R_{t1} + R)\, I_s + (L_s + L_{t1} + L_{t2} + L_{af})\,\frac{dI_s}{dt} \qquad 3.2$$

and

$$V_p = V_s - (R_s + R_{t1})I_s \_ (L_s + L_{t1})\frac{dIs}{dt} \qquad 3.3$$

The differential equations are now converted to linear state equations of the type ,

$$\dot{X} = AX + BU \qquad 3.4$$

and

$$Y = CX + DU \qquad 3.5$$

where ,

X = Is , Y = Vp , U = Vs .

$$A = -\frac{(R_s + R_{t1} + R)}{(L_s + L_{t1} + L_{t2} + L_{af})} \quad , \quad B = \frac{1}{(L_s + L_{t1} + L_{t2} + L_{af})}$$

$$C = -R_t\left(1 + \frac{(L_s + L_{t1})}{(L_s + L_{t1} + L_{t2} + L_{af})}\right) \quad , \quad D = \left(1 - \frac{(L_s + L_{t1})}{(L_s + L_{t1} + L_{t2} + L_{af})}\right)$$

The system can now be solved on Matlab by converting it into a discrete model in the time domain .

3.5 Variations of different parameters during initial period of the melt .

The system is solved for a period of 1.5 sec. so as to obtain harmonic spectrum upto a frequency of 1Hz required to evaluate flicker on the critical bus , the different waveforms and their analysis is given below .

3.5.1 The Arc current and its harmonic spectrum .

The Arc current fluctuates considerably and has a large harmonic content as shown in the figure 3.3 .It is quite clear from the figure that the current has some low frequency random modulations which are the main cause of flicker .The rms value of the current also changes randomly leading to a deteriorating voltage profile at the critical bus .

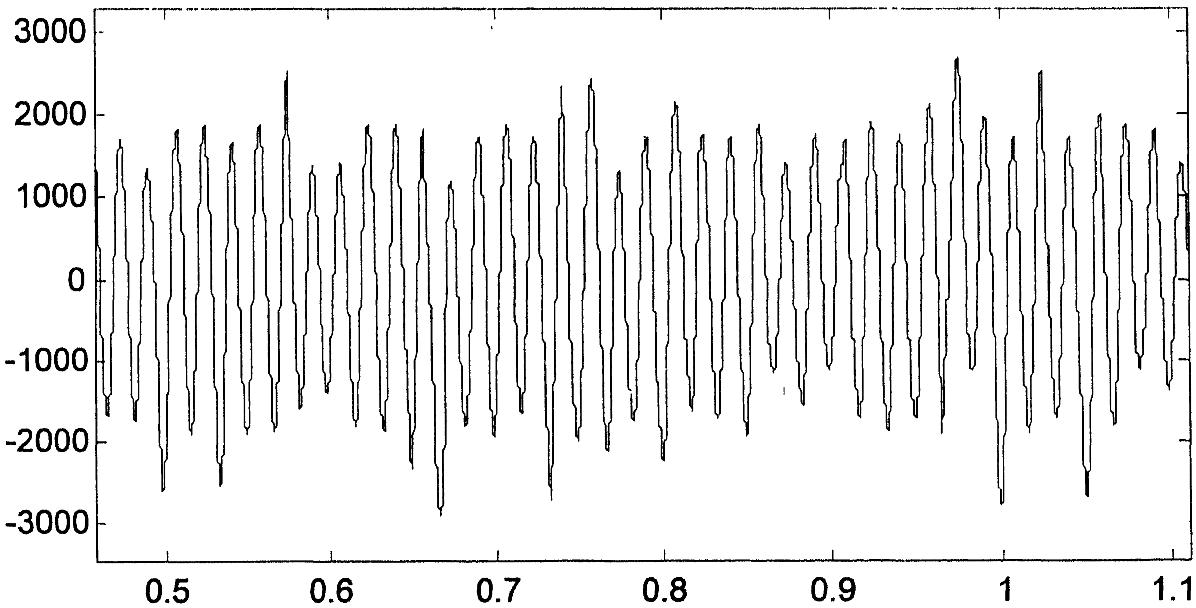


Figure 3.3 : Arc current waveform

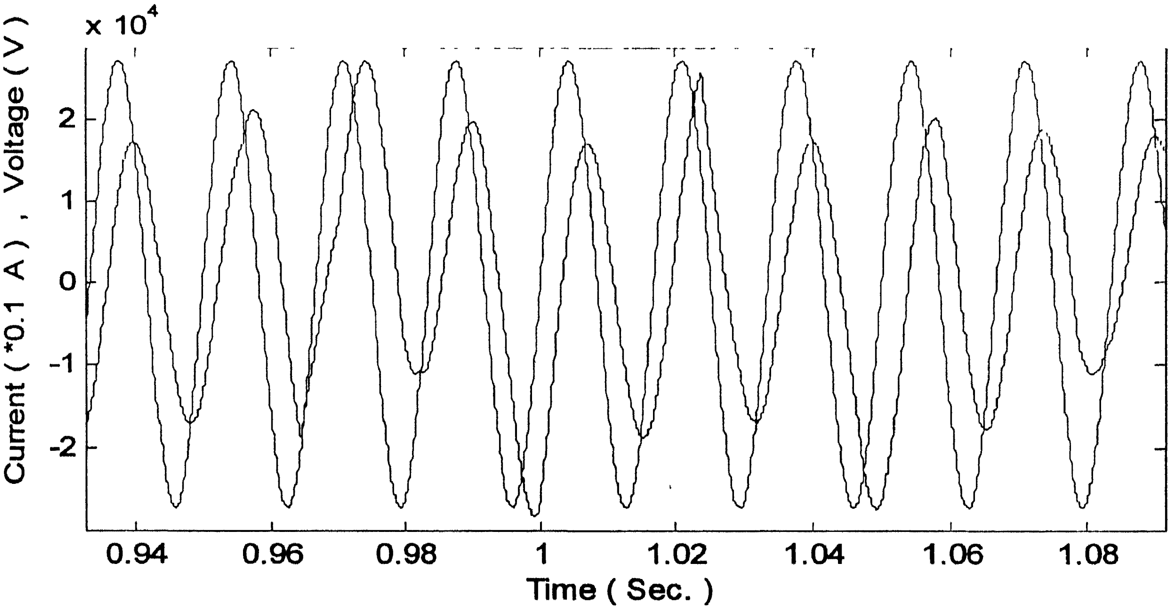


Figure 3.4 : Load current and source voltage

We can see from the figure 3.4 that the source current lags the voltage by a large amount and hence there is strong need of compensation of some type to reduce that level.The spectrum of source current shown in figure 3.5 also highlights the strong need of compensation .

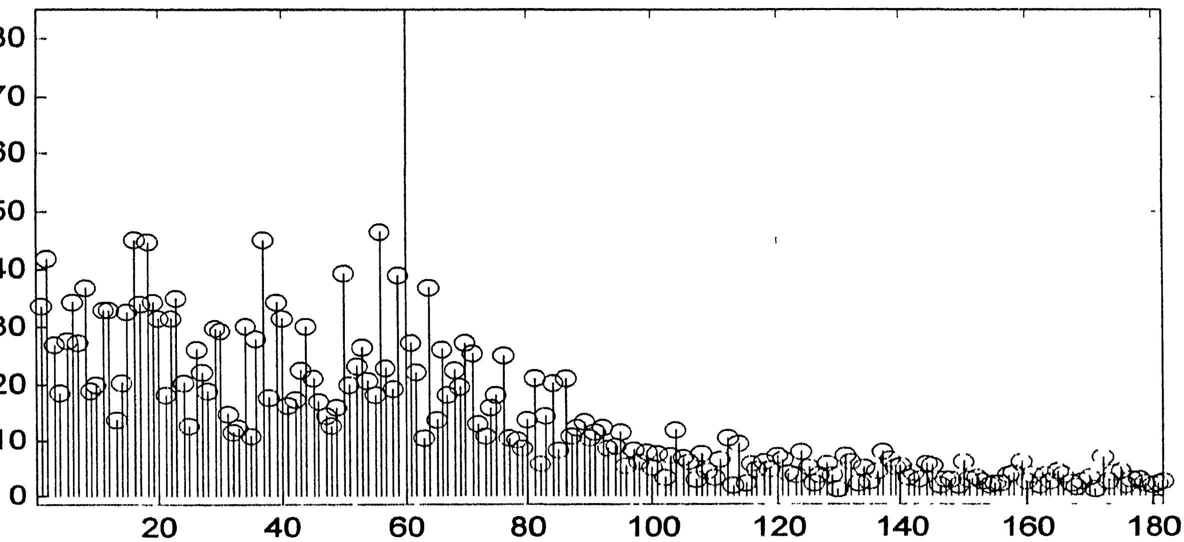


Figure 3.5 : Load current spectrum

3.5.2 Real and reactive power drawn by the arc furnace

The following plots shows the variations of real and reactive power drawn by the arc furnace.

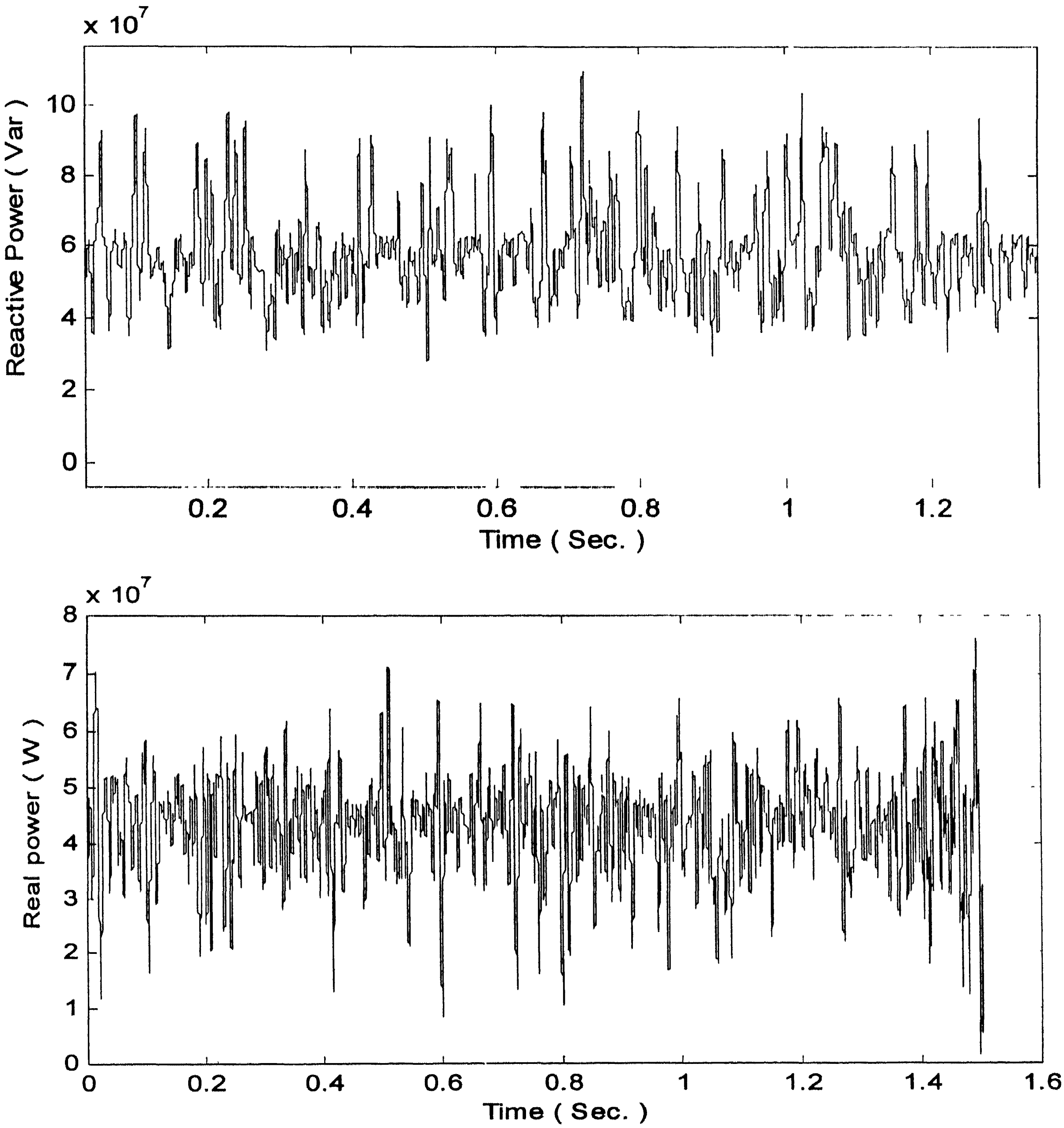


Figure 3.6 : Load real and reactive power

Figure 3.6 indicates that the real and reactive power drawn by the load fluctuates tremendously thus highlighting the importance of the requirement of some form of compensation or else the supply system may suffer from disturbances .

3.5.3 Voltage at the critical bus .

The following plots shows the variation of the voltage at the critical bus with respect to the supply system voltage .

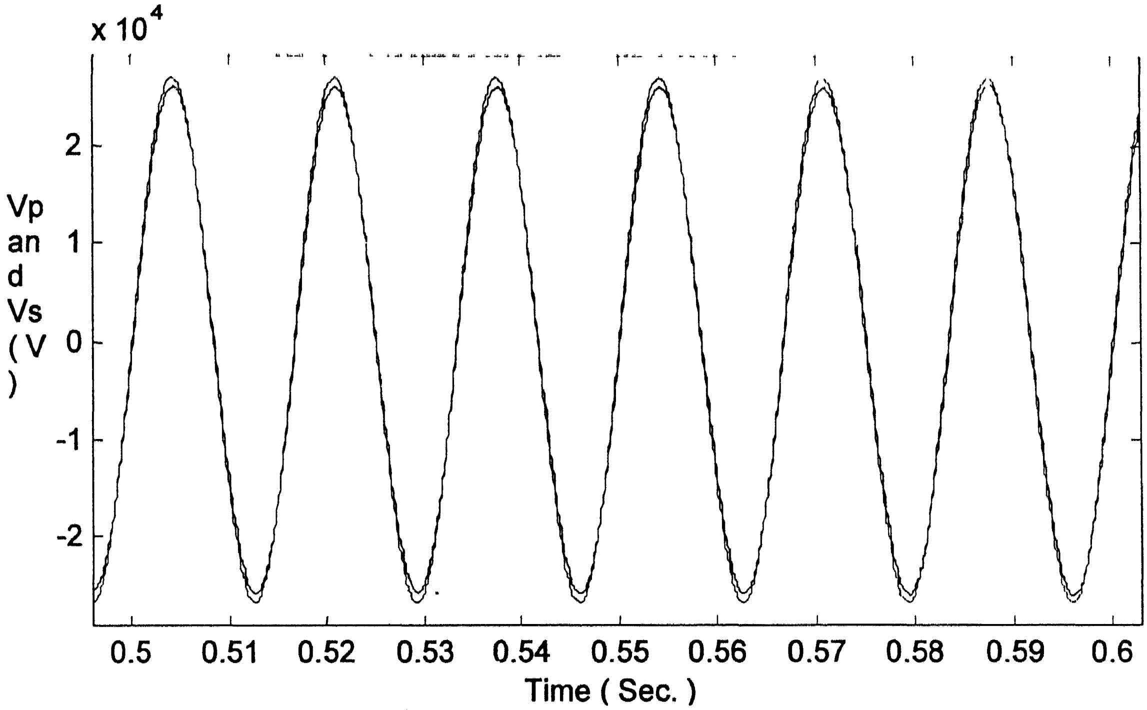


Figure 3.7 : Source and critical bus voltage

It can be seen from the figure that the phase voltage can drop by as much as 5 % of the rated supply voltage .Further it is clear from the next plot that the voltage fluctuations have a high harmonic content at low frequencies particularly below 30 Hz , giving rise to flicker .

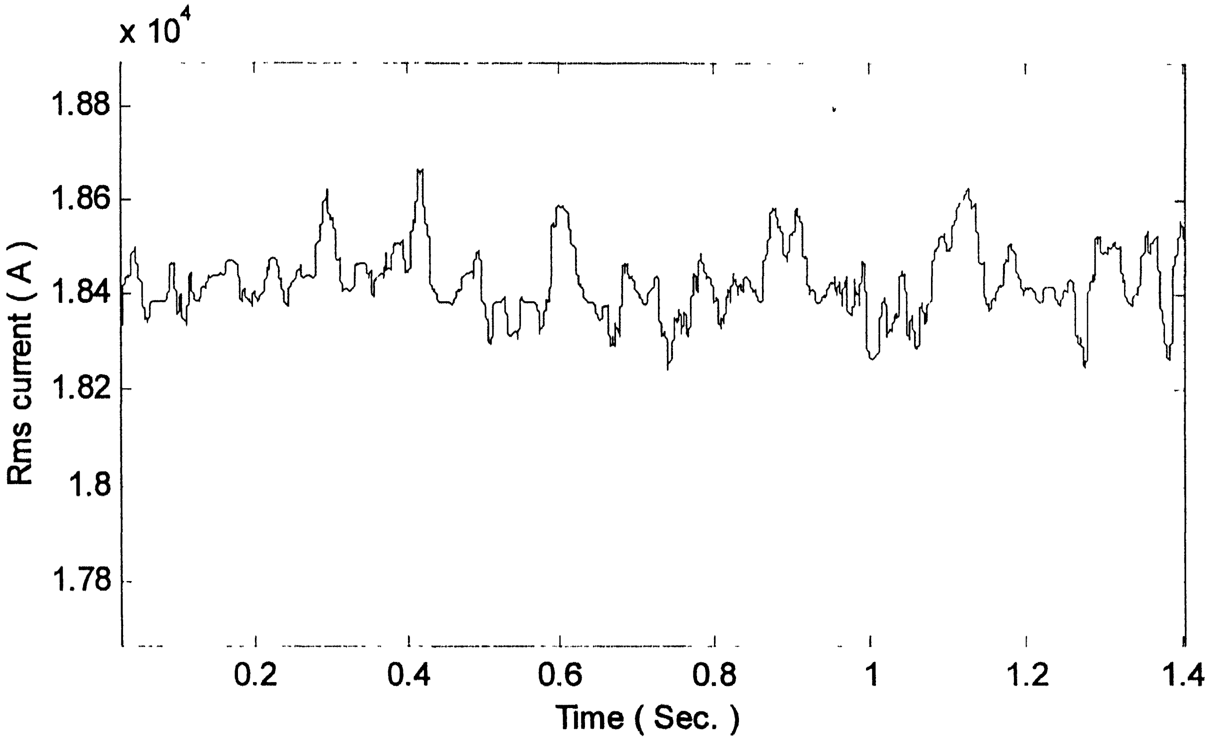


Figure 3.8 : r.m.s voltage at the critical bus

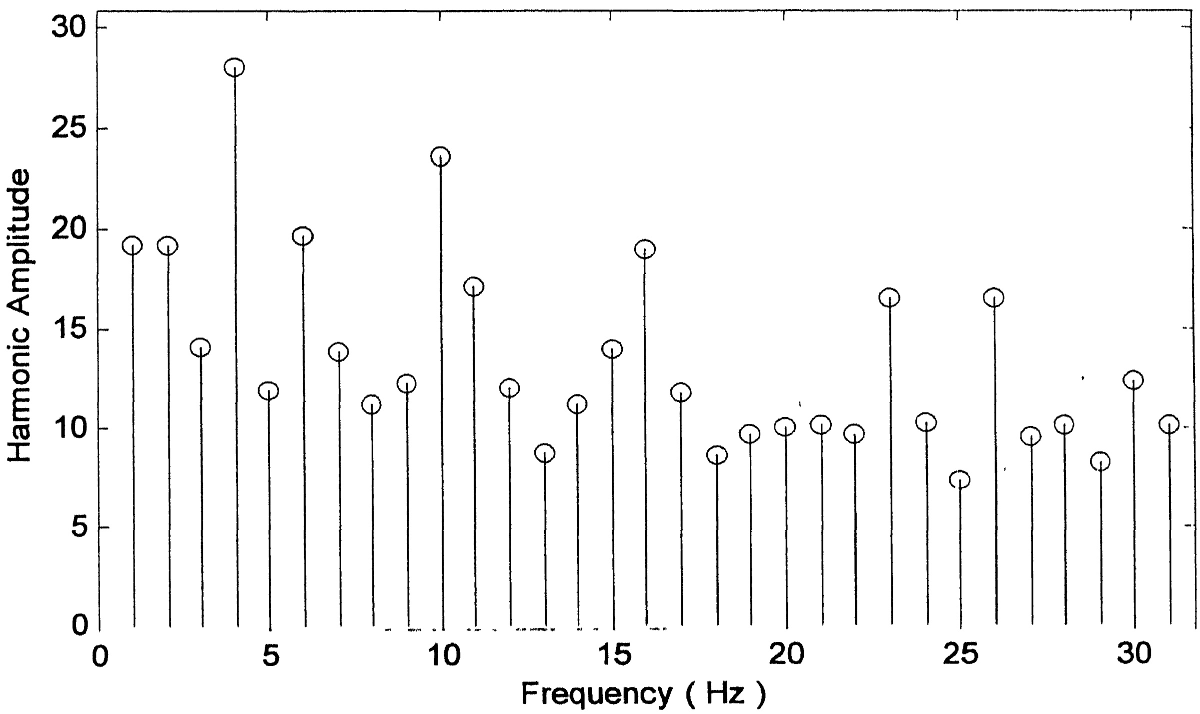


Figure 3.9 : Harmonic spectrum of the voltage at the critical bus

3.5.4 Evaluation of flicker on the critical bus .

Flicker has been already defined in the previous section. Taking that definition and the above spectrum for voltage fluctuations we have

$$\Delta V_{10} = \left\{ \sum_{n=1}^{30} (a_n . \Delta V_n)^2 \right\}^{1/2}$$

where,

a_n = Sensitivity coefficient of human eye at frequency fn .

ΔV_n = Harmonic amplitude at frequency fn .

The flicker level level for this uncompensated case turns out to be 58.5 .

3.6 Conclusions

It is seen that the arc furnace indeed behaves in a very random fashion. The arc current contains a large amount of harmonics thus leading to a poor voltage profile at the critical bus. The power factor is also very poor and the level of flicker is very high.

Thus we can conclude that an arc furnace just cannot be operated without any compensating elements. It has also been shown that the furnace parameters vary randomly and at times very quickly, hence we need a compensation scheme that is fast enough to compensate the arc furnace effectively and reduce the flicker to acceptable levels.

Chapter 4

COMPENSATION OF ARC FURNACE WITH S.V.C

4.1 Introduction

The capacity of arc furnaces have risen at a sharp rate in the recent years, as a result, the problem of flicker has become quite acute. Traditionally, rotating synchronous condensers were used in order to compensate for the reactive power and reduce flicker.

In recent years however, static V.A.R. compensators using thyristors have superceded the synchronous condenser for the following reasons,

1 Fast response (within a half cycle).
2 Low maintenance costs.
3 Superior efficiency and lower losses.

V.A.R compensation using thyristors have the following benefits besides flicker reduction.

1 Improves the overall power factor.
2 Reduces the harmonic currents.
3 Reduces losses by eliminating the reactive current.

This chapter investigates the effects of a shunt installed S.V.C., comprising of a fixed capacitor and thyristor switched reactor, on the operation and characteristics of arc furnace installation.

4.2 Basic performance of a S.V.C.

The basic idea of S.V.C. is to control the reactive component of the source current, through compensating the load, by controlling the current through a reactor with the help of thyristor switches. Two anti-parallel thyristors Th1 and Th2 are connected in series with an inductor L, as shown in the figure 4.1. We also have a capacitor in parallel with this reactor branch so as to make it work as an effective capacitor.

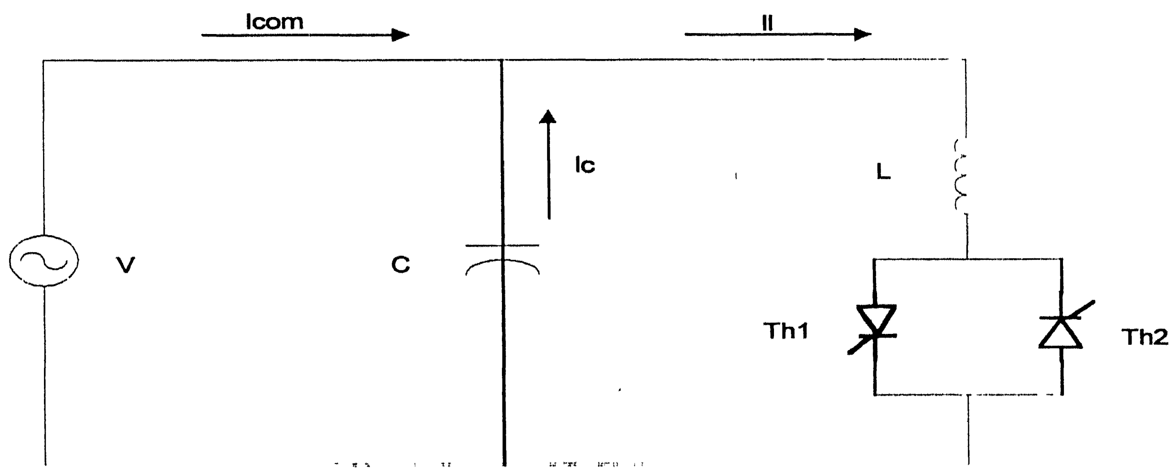


Figure 4.1 : Principle of operation of a S V.C

Thyristors Th1 and Th2 are made to conduct by means of a trigger signal, the duration and peak of current is regulated by the variable angle of delay of the trigger signal, α, with respect to the peak of the phase voltage. This is shown in the figure 4.2,

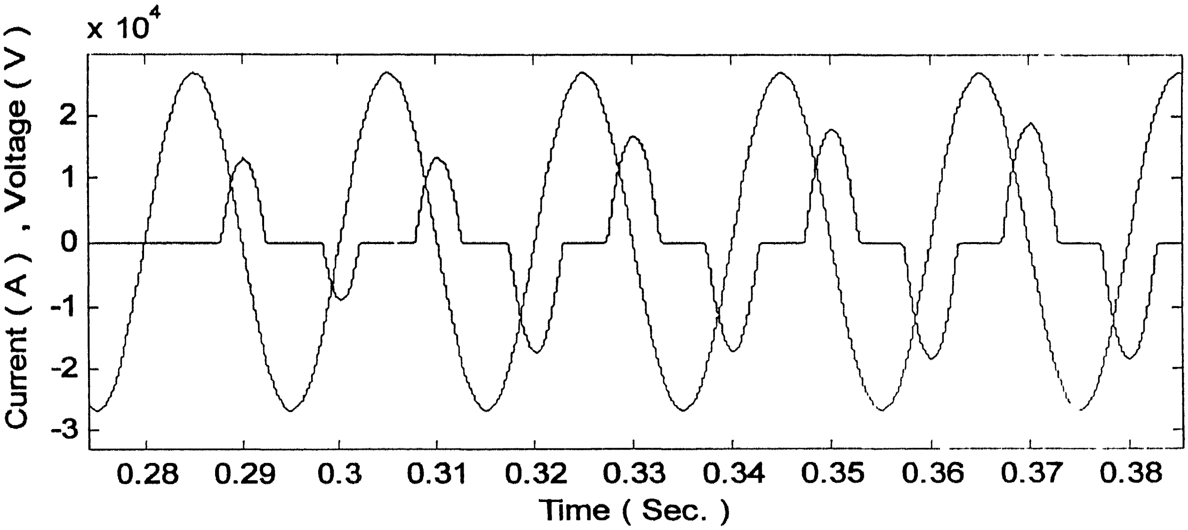


Figure 4.2 : Thyristor current for different firing angles and source voltage

Hence we can say that with the help of the thyristor switch we can control the reactor current and in effect control the reactive power drawn by the inductor.

The reactor current at a firing angle delay of α with respect to the voltage peak is given by the following equation,

$$i_l(t) = I_{lo}\{\sin(w \cdot t) - \sin(\alpha)\} \qquad \text{if} \qquad \alpha \leq w \cdot t \leq (\pi - \alpha) \qquad 4.1$$

where ,

$I_{lo} = \dfrac{V_o}{w \cdot L}$ = peak value of reactor current at zero firing angle .

V_o = peak value of the supply voltage .

The fundamental component of the reactor current at firing angle α is given by the following expression,

$$I_{lf}(\alpha)=\frac{2}{\pi}\left\{\left(\frac{\pi}{2}\right)-\alpha-\frac{\sin(2\alpha)}{2}\right\} \qquad 4.2$$

The firing angle at rated reactor current is called α_o. The selection of α_o depends upon the tradeoff between the flicker compensating effect and harmonics generated by the reactor itself. For the purpose of this study α_o has been taken as 30^0 this implies that the firing angle can now vary from this value to 90^0.

Using a fixed capacitor in parallel with the thyristor switched reactor makes the complete unit work as an effective variable reactive power source. The total compensator current is the resultant of the capacitor current and the reactor current and is given by,

$$I_{comp}(t)=I_c(t)+I_l(t) \qquad 4.3$$

where ,

$$I_c(t)=-I_{co}\sin(w\cdot t)$$

where $\quad I_{co}=V_o\cdot w\cdot C$

and $\quad I_l(t)$ is given by the previous equation .

The fundamental component of the total compensator current is given by,

$$I_{comf}(\alpha)=I_c-I_{lo}+\left(\frac{2}{\pi}\right)I_{lo}\left\{\alpha-\frac{\sin(2\alpha)}{2}\right\} \qquad 4.4$$

4.3 Measurement and control

In this type of V.A.R compensators, it is important to measure the reactive power variations of the arc furnaces precisely and control the thyristor current as rapidly as possible to accomplish good compensation.

The principle of measuring and control state that the active current i_p of the arc furnaces be measured by multiplying the instantaneous value of i at the peak of the voltage by a unit sinusoidal wave in phase with the voltage and the reactive component can be detected continuously by subtracting i_p from i i.e. $i_q = (i - i_p)$.

Another way to measure the required fundamental reactive current I_q is that we continue evaluating the average reactive power demanded by the load for the last half cycle by the moving average technique and estimate the required reactive current by dividing the reactive power required by the load with the rms voltage at the bus .

When the furnace current changes abruptly the measuring signal 'IQ', equal to the fundamental component of the reactive part of furnace current for the last half cycle, also follows the changes immediately. The firing instants for the next half cycle are generated by evaluating the crosspoint of 'IQ' and the function 'F' which represents the relation of the fundamental compensating current and the firing angle as shown below in figure 4.3,

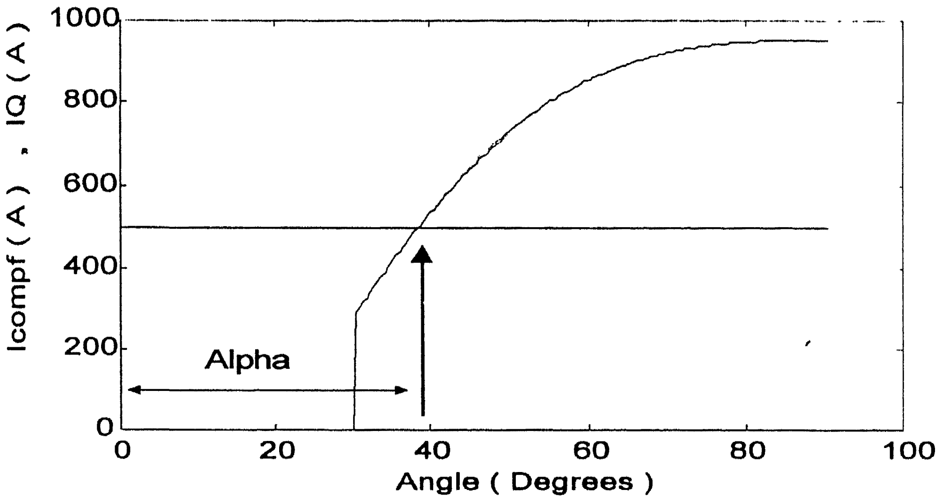


Figure 4.3 : Comparing IQ and I_{compf} to obtain the firing angle

Thus it is clear that we can compensate for the fundamental reactive current of the arc furnace for each half cycle in the next half cycle.

4.4 System outline and state equations

The system that has been considered for compensation in none other than the one considered in chapter 3 except for the addition of an S.V.C on the 33kV bus. The figure

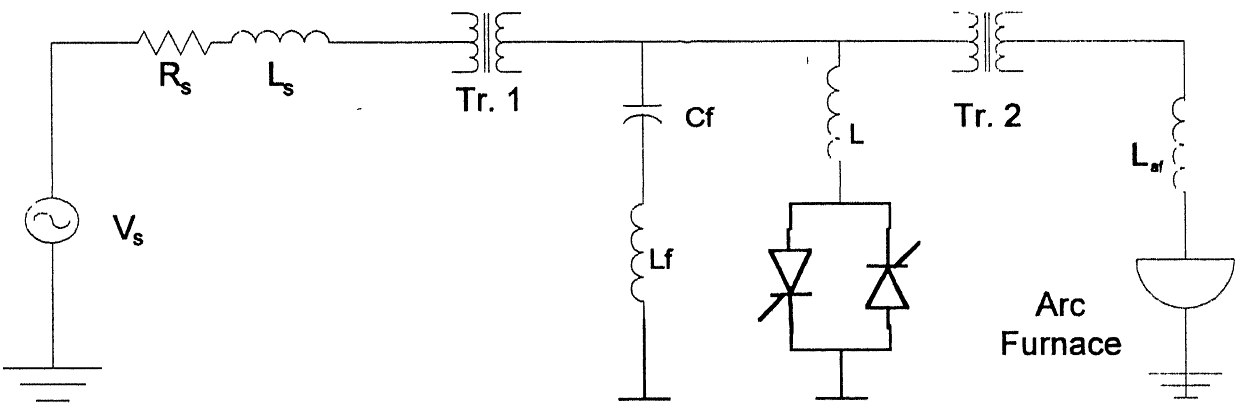


Figure 4.4 : Single line diagram of the arc furnace installation

4.4 shows the single line diagram for the arc furnace installation being considered for compensation.

The single phase equivalent of the system along with the values of all the parameters is given in the figure 4.5 shown below.

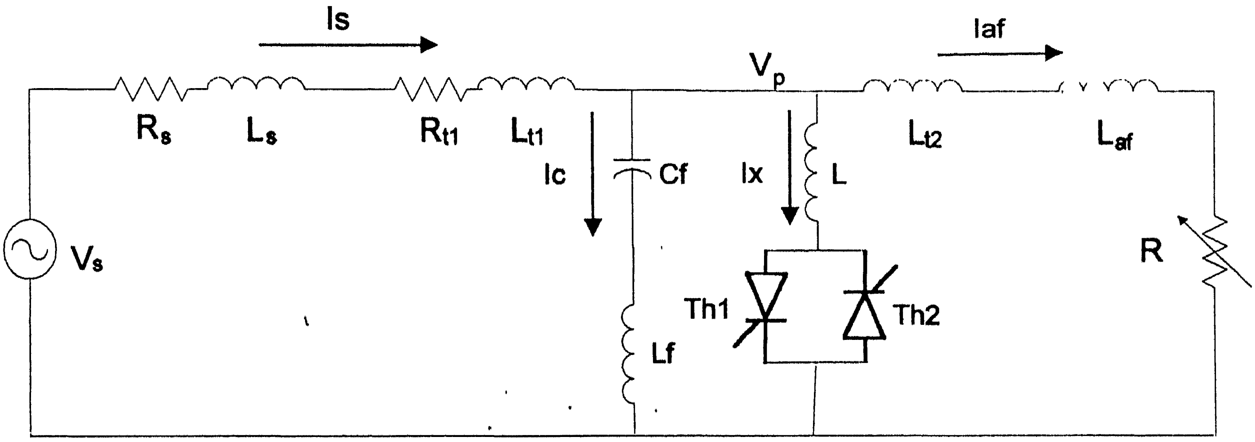


Figure 4.5 : Single phase equivalent of the arc furnace system

The values of S.V.C parameters are as follows,

Cf = 0.1 mF Lf = 5 mH L = 50mH

The differential equations governing the system are as follows,

Case 1 : If any of the thyristors is conducting ,

$$V_s = (R_s + R_{t1}) \cdot i_s + (L_s + L_{t1})\frac{di_s}{dt} + (R) \cdot i_{af} + (L_{t2} + L_{af})\frac{di_{af}}{dt} \qquad 4.5$$

$$V_s = (R_s + R_{t1}) \cdot i_s + (L_s + L_{t1})\frac{di_s}{dt} + L\frac{di_x}{dt} \qquad 4.6$$

$$V_s = (R_s + R_{t1}) \cdot i_s + (L_s + L_{t1})\frac{di_s}{dt} + V_c + L_f \frac{di_c}{dt} \tag{4.7}$$

$$i_c = C_f \frac{dV_c}{dt} \tag{4.8}$$

Case 2 : When none of the thyristors is conducting ,

All of the above equations are valid except the second. But then the number of state variables also reduces to three because of elimination of Ix. Hence in that case also the system can be solved with three equations at hand.

The above equations can be solved by converting them to state equations of the type ,

$$\begin{aligned} \dot{X} &= AX + BU \\ Y &= CX + DU \end{aligned} \tag{4.9}$$

where X is the state vector with four state variables and U is the input function that is the system voltage , A , B , C , D are system màtrices which are given below ,

$$X = \begin{pmatrix} V_c \\ i_{af} \\ i_c \\ i_x \end{pmatrix} \qquad Y = (V_p)$$

further ,

if none of the thyristors is conducting ,

$$A = \begin{bmatrix} 0 & 0 & \dfrac{1}{C_f} & 0 \\ \dfrac{M_1}{(L_T M_1 - 1)} & \dfrac{M_2}{(L_T M_2 + R + R_T)} & \dfrac{M_3}{L_T M_3} & 0 \\ L_f & L_f & L_f & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad B = \begin{bmatrix} 0 \\ M_5 \\ \dfrac{L_T M_5}{L_f} \\ 0 \end{bmatrix}$$

and if any of the thyristor is conducting ,

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \dfrac{M_1}{(L_T M_1 - 1)} & \dfrac{M_2}{(L_T M_2 + R + R_T)} & \dfrac{M_3}{L_T M_3} & \dfrac{M_4}{L_T M_4} \\ L_f & L_f & L_f & L_f \\ \dfrac{L_T M_1}{L} & \dfrac{(L_T M_2 + R + R_T)}{L} & \dfrac{L_T M_3}{L} & \dfrac{L_T M_4}{L} \end{bmatrix} \qquad B = \begin{bmatrix} 0 \\ M_5 \\ \dfrac{L_T M_5}{L_f} \\ \dfrac{L_T M_5}{L} \end{bmatrix}$$

and for both of the above cases ,

$$C = \begin{bmatrix} L_T M_1 \\ L_T M_2 + R + R_T \\ L_T M_3 \\ L_T M_4 \end{bmatrix} \qquad D = [L_T M_5]$$

where ,

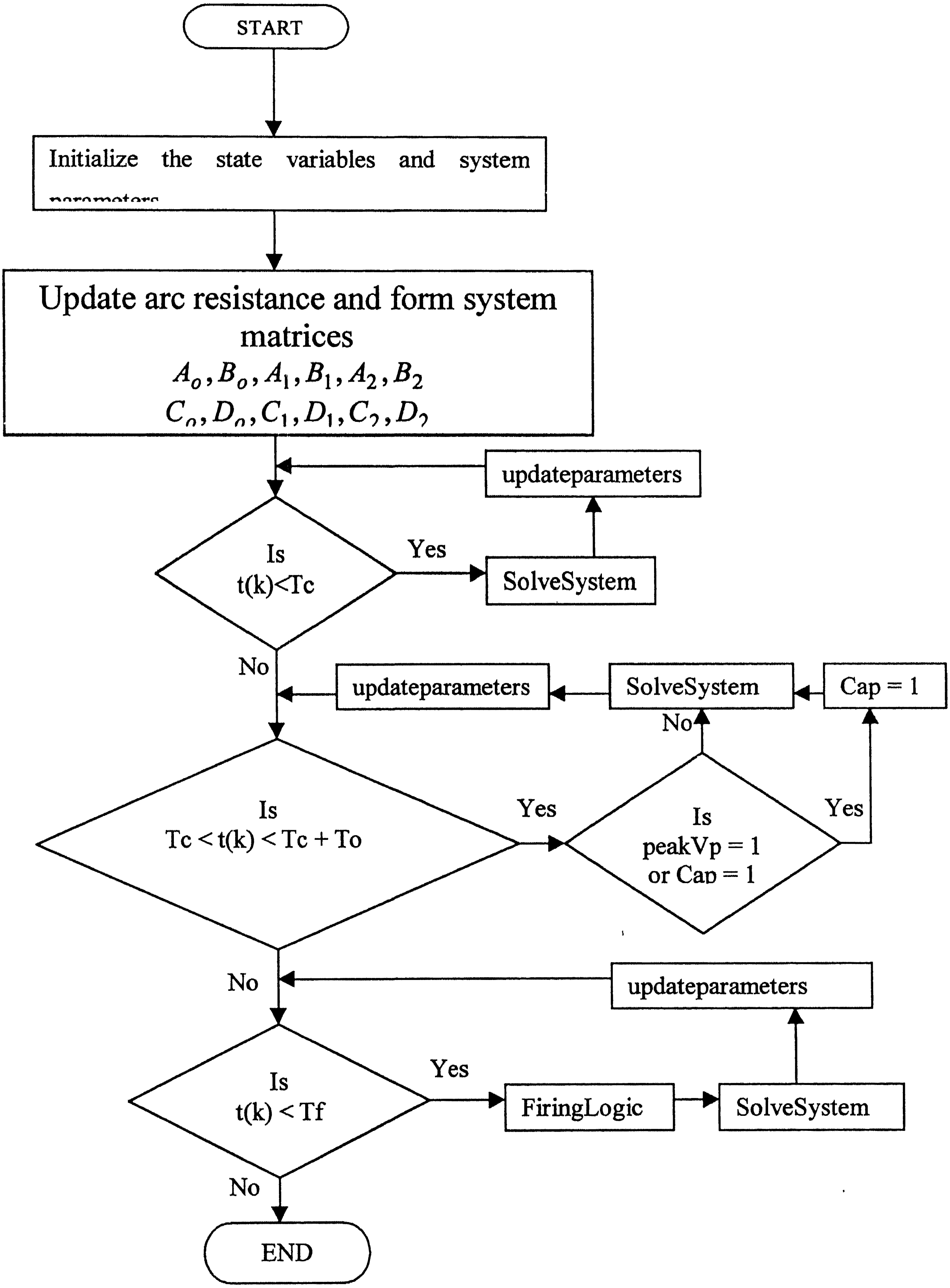
	Thyristors not conducting	Thyristors conducting
D	$L_S L_T\left(\frac{1}{L_f}+\frac{1}{L_S}+\frac{1}{L_T}\right)$	$L_S L_T\left(\frac{1}{L_f}+\frac{1}{L_S}+\frac{1}{L_T}+\frac{1}{L}\right)$
M_1	$\frac{L_S}{(L_f \cdot D)}$	$\frac{L_S}{(L_f \cdot D)}$
M_2	$-\frac{1}{D}\left\{R_S+\left(\frac{L_S}{L_f}+1\right)(R+R_T)\right\}$	$-\frac{1}{D}\left\{R_S+\left(\frac{L_S}{L_f}+\frac{L_S}{L}+1\right)(R+R_T)\right\}$
M_3	$-\frac{R_S}{D}$	$-\frac{R_S}{D}$
M_4	0	$-\frac{R_S}{D}$
M_5	$\frac{1}{D}$	$\frac{1}{D}$

Here in the above expressions,

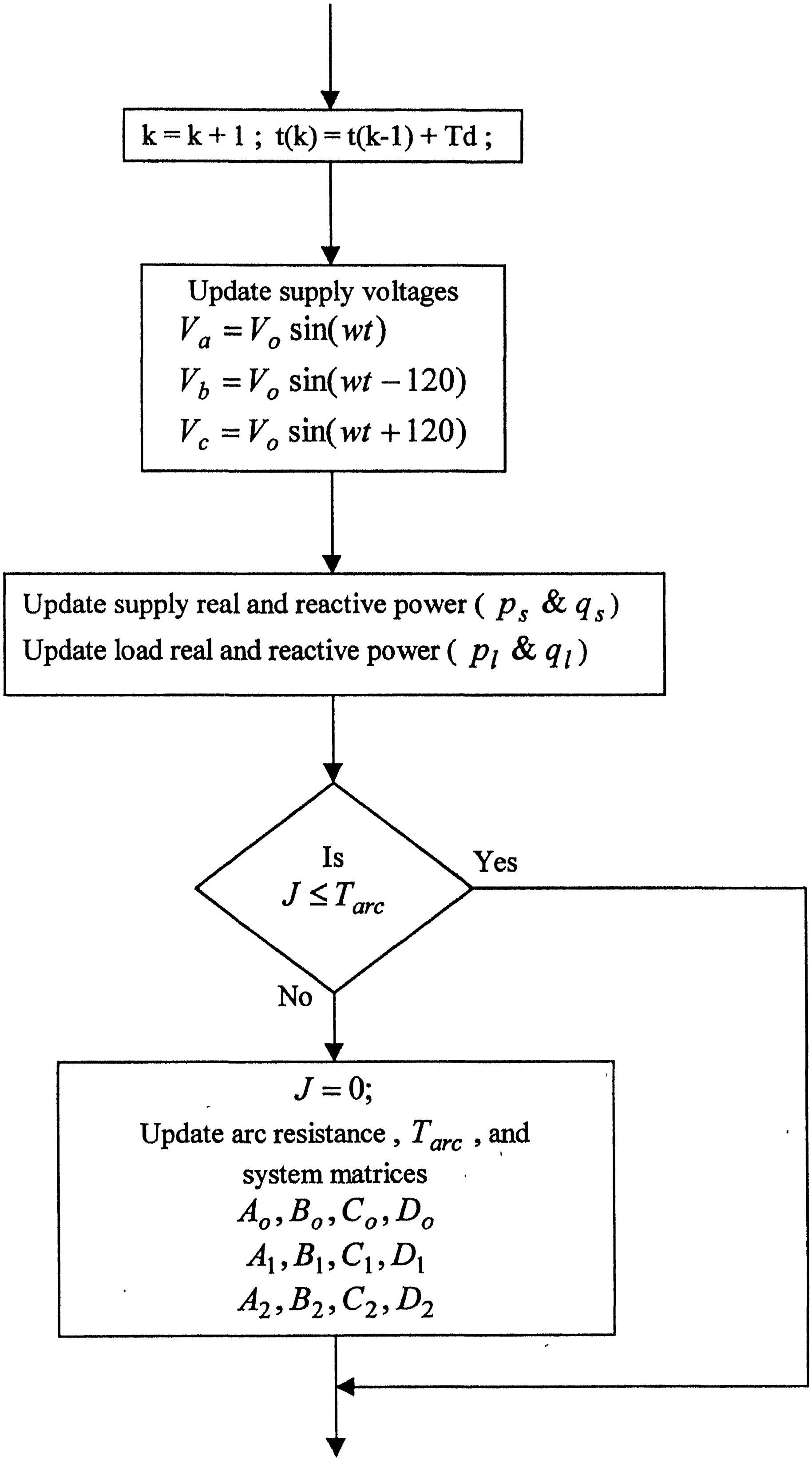
$$R_S = R_s + R_{t1} \qquad L_S = L_s + L_{t1}$$

$$R_T = R_{t2} \qquad L_T = L_{t2} + L_{af}$$

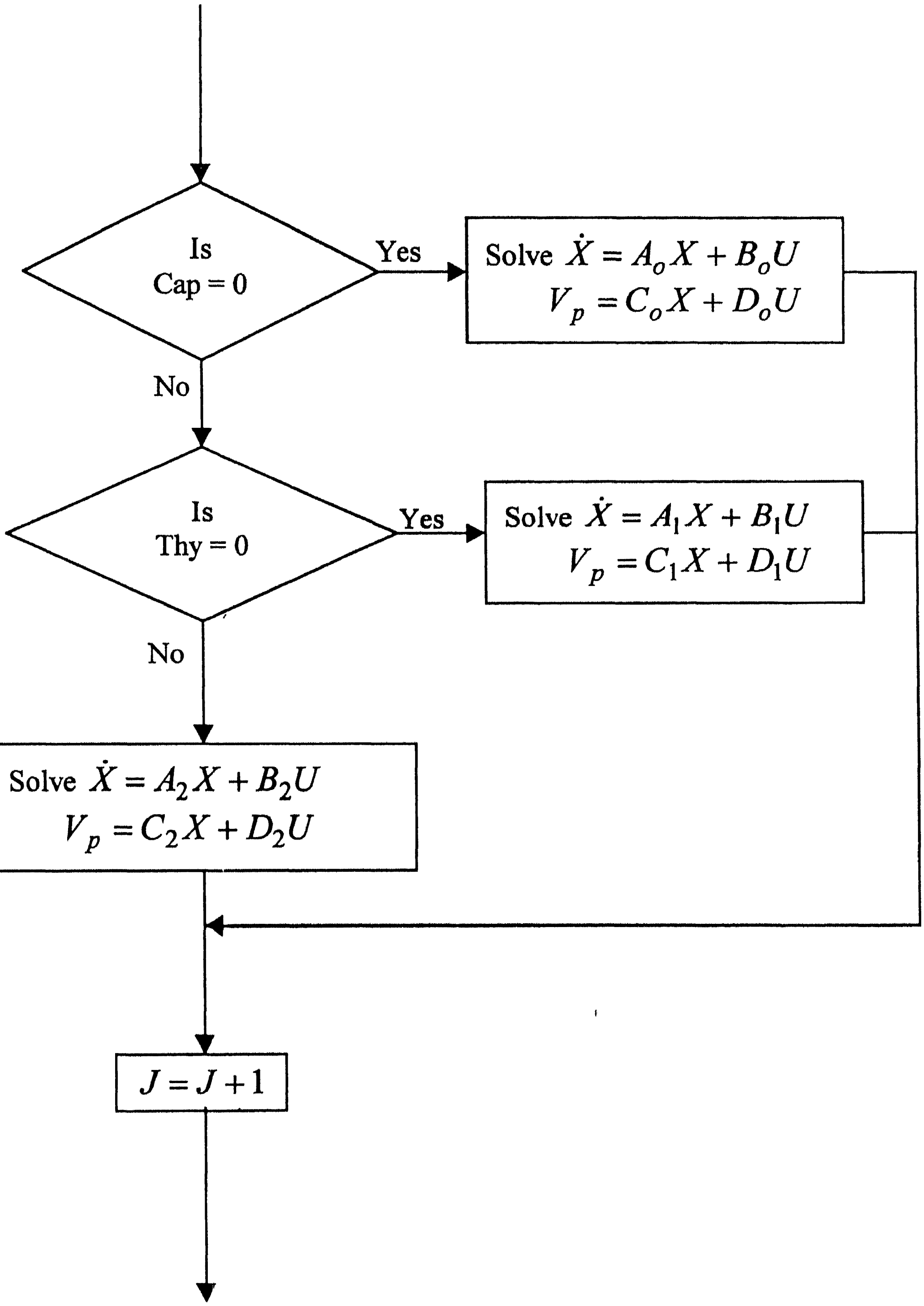
4.5 Flowchart for the system with S.V.C



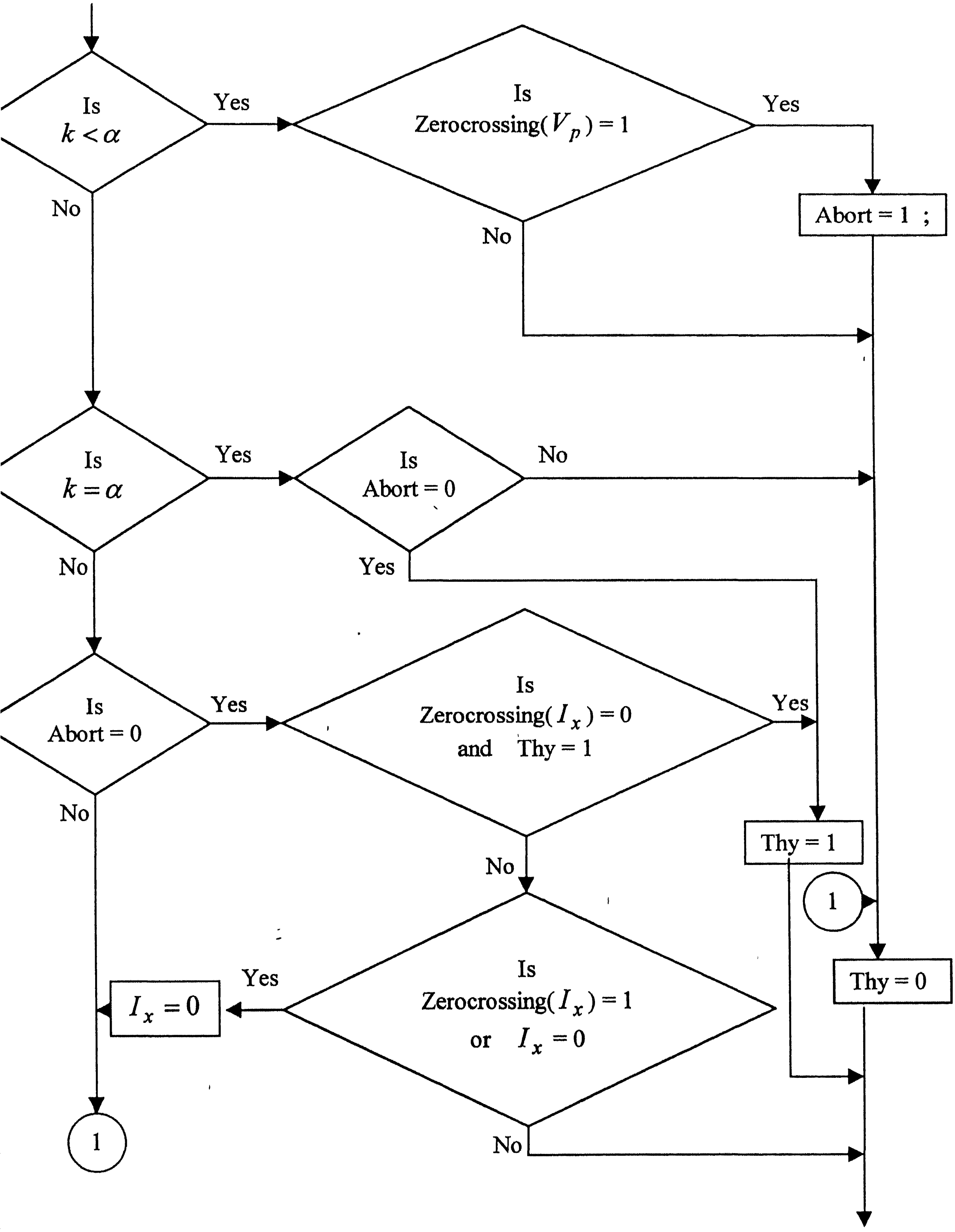
4.5.1 Flowchart for the function updateparameters



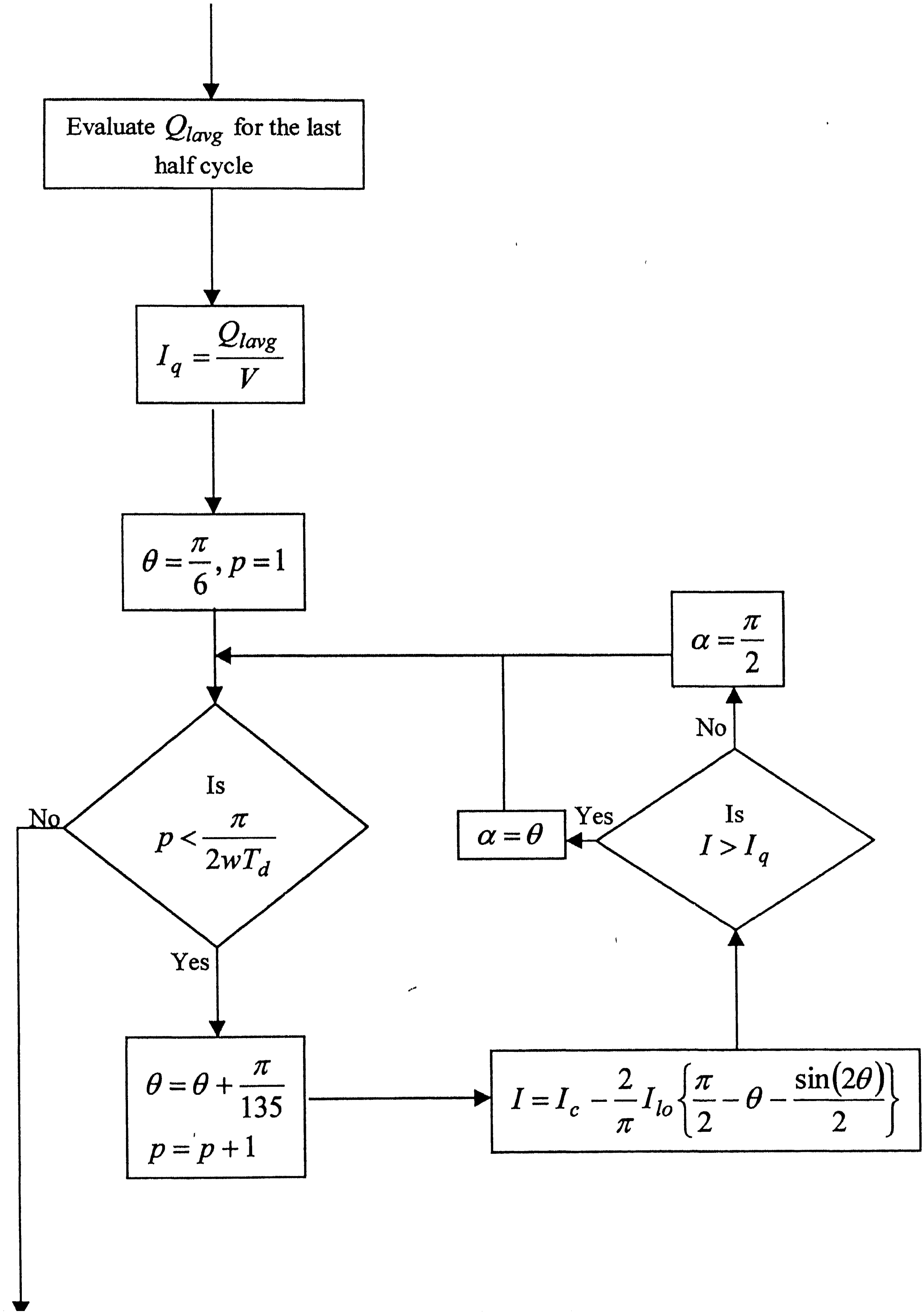
4.5.2 Flowchart for the function SolveSystem



4.5.3 Flowchart for the function FiringLogic



4.5.4 Flowchart for the function UpdateAlpha



4.6 Performance of arc furnace with S.V.C in parallel

The rest of this chapter deals with evaluating the performance of the arc furnace with a S.V.C in parallel.

4.6.1 Arc current and source current waveform and spectrum

The waveform shown below indicates that we do have significant reduction in the mean r.m.s value of the current being supplied by the source basically because of compensation of the average reactive current required by the arc furnace. It can also be seen that we do not have very good compensation as the source current, though less in magnitude, still varies quite a lot and has a large harmonic spectrum as indicated in the figure 4.6 given below.

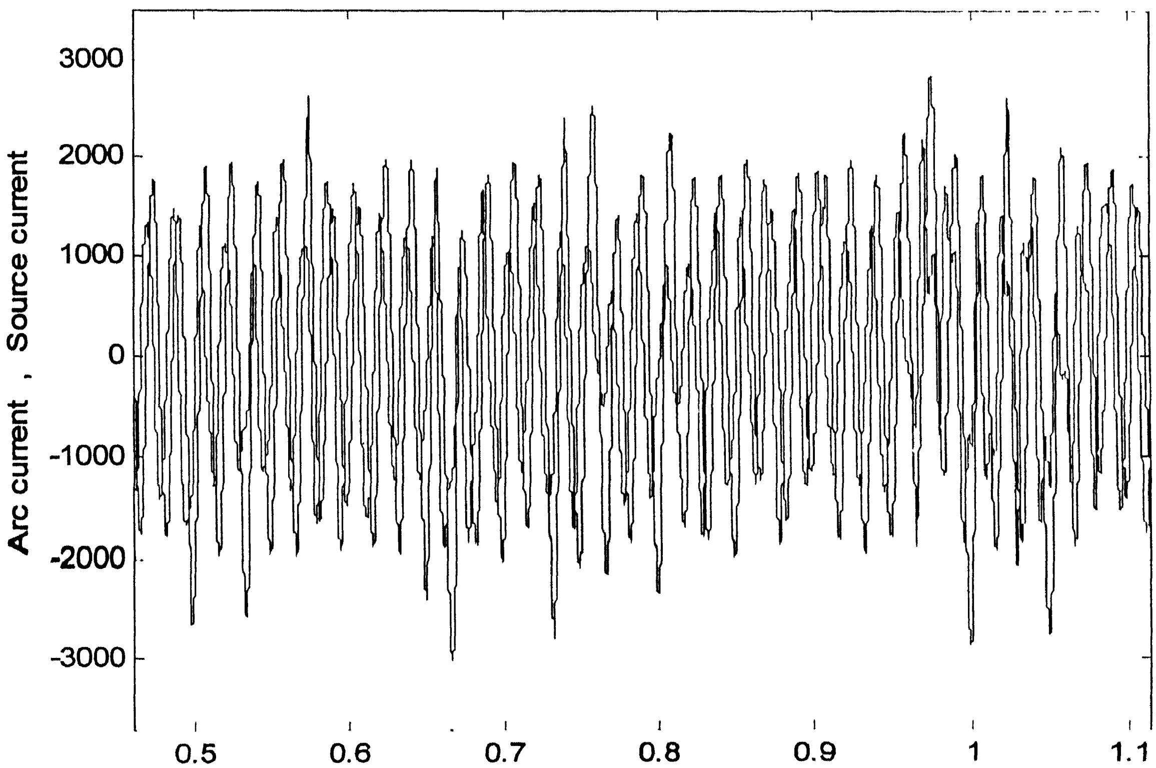


Figure 4.6 : Load and source current waveforms

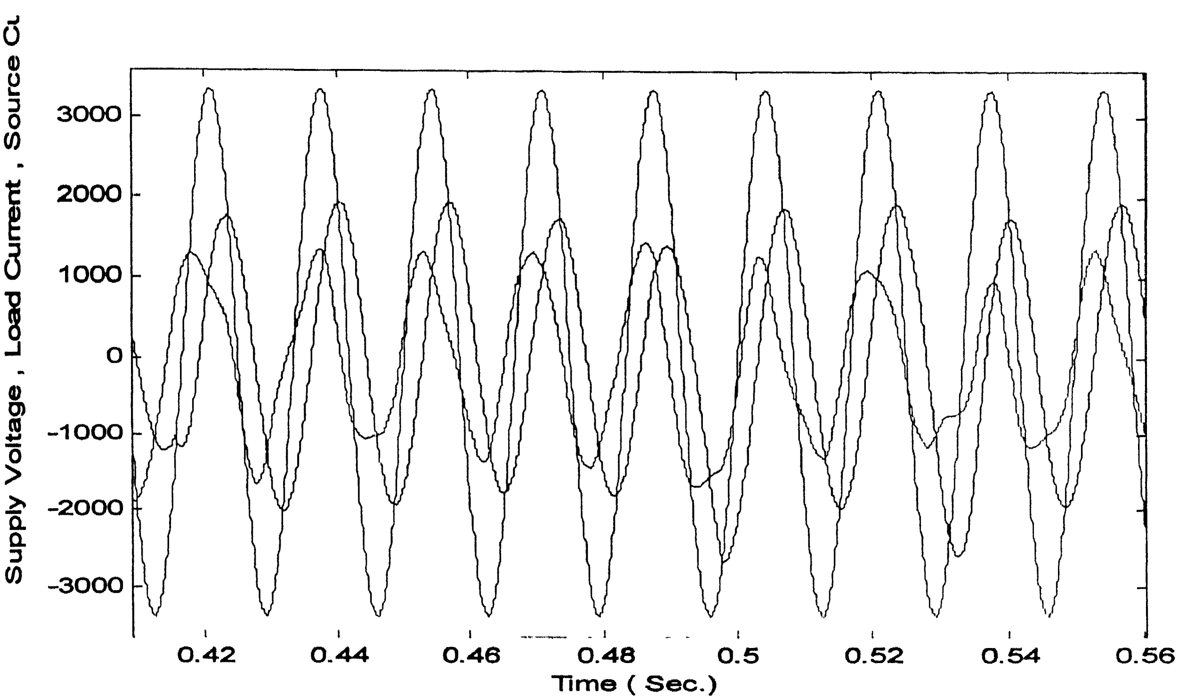


Figure 4.7 : Load and source current along with source voltage

It can be clearly seen from the figure 4.7 given above that the supply current, though not sinusoidal indeed is almost in phase or leads slightly owing to the capacitor connected in parallel. This is probably the best we can do with a S.V.C because it cannot be controlled in less than a half cycle and hence is inherently incapable of compensating ideally such a rapidly changing load.

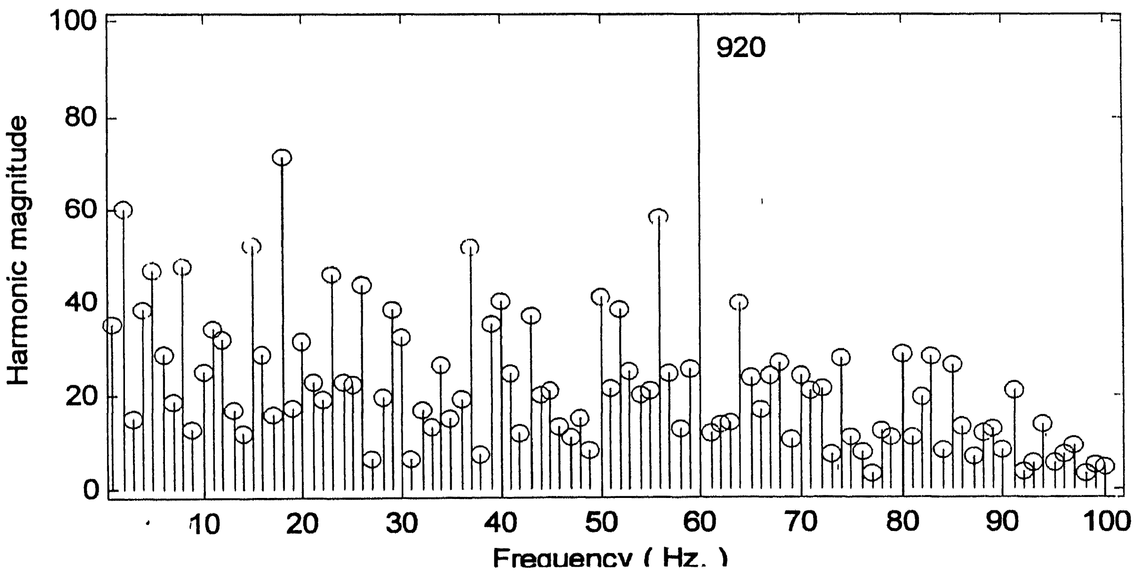


Figure 4.8a : Load current harmonic spectrum

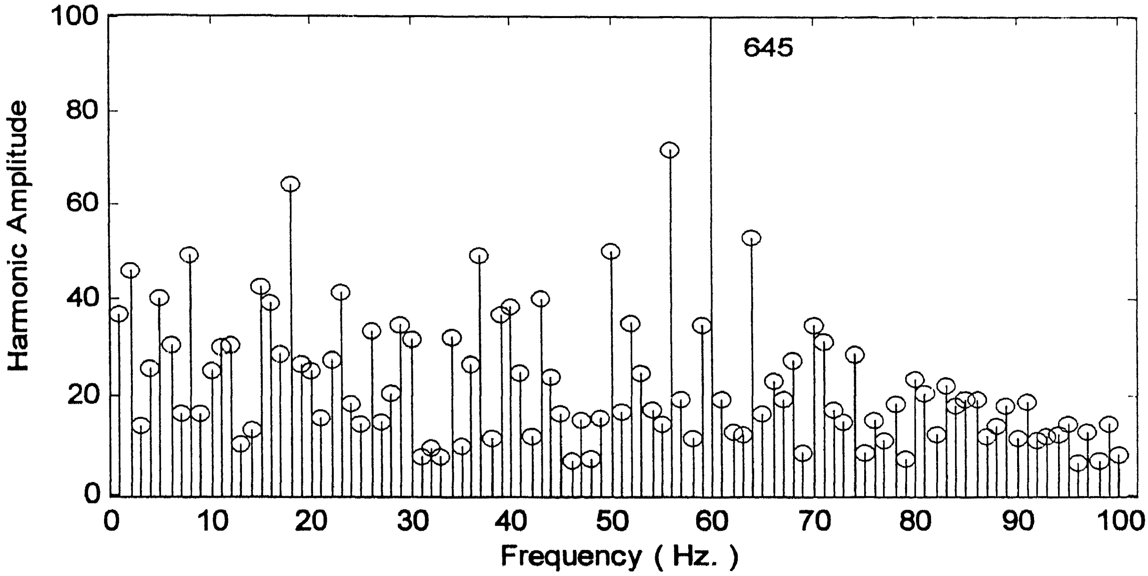


Figure 4.8b : Source current spectrum

From the figures 4.8a and 4.8b given above we can see that we do have some limited improvement in the spectrum at frequencies other than 60 Hz. We are particularly worried at lower frequencies because they are the main cause of flicker problem. Hence it can be asserted that a S.V.C is a bit slow to efficiently compensate an arc furnace.

4.6.2 Real and Reactive power

The figures 4.9 and 4.10 given below indicate the significant reduction in the demand of reactive power from the supply as a result of compensation with a S.V.C .It can also be seen that the fast variations in the reactive power demand are not suppressed to a great extent although on an average basis the demand has reduced drastically .

Thus it can be said that though a S.V.C might be a good compensator for other loads but it is definitely not so with arc furnaces. The variations for arc furnaces are wild and random, and hence they are far too fast for the S.V.C to respond.

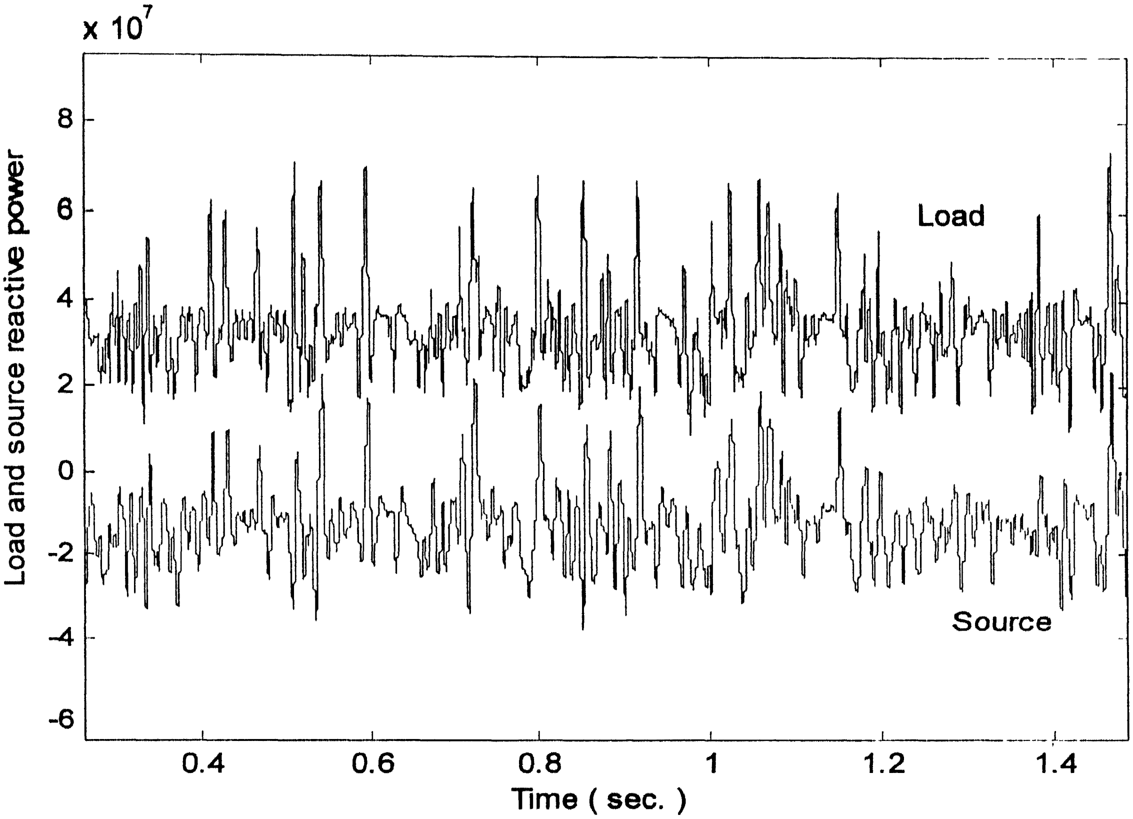


Figure 4.9 : Load and source reactive power

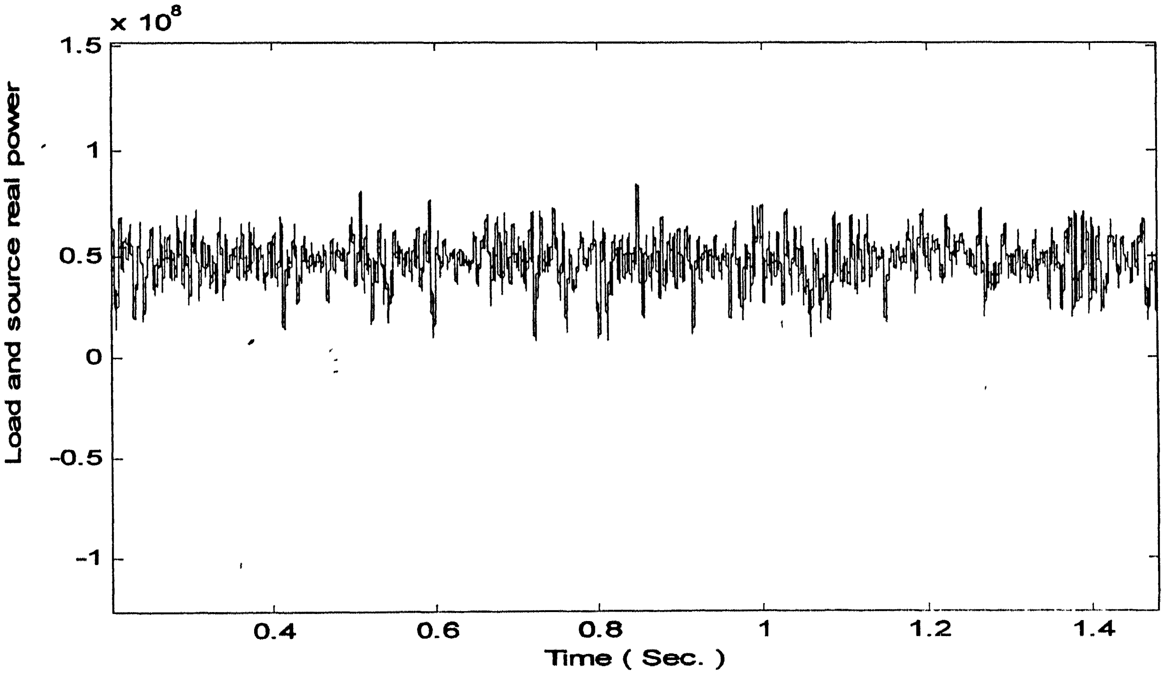


Figure 4.10 : Load and source real power

As for the real power, it also varies randomly along with the arc resistance. As we have compensated only for the fundamental reactive power hence all the real and reactive harmonic power is still derived from the source hence resulting in such a waveform.

4.6.3 Voltage and its spectrum at the critical bus

As shown in the previous chapter, the voltage at the critical bus fluctuates whenever the arc furnace is in operation, thus resulting in flicker. When an S.V.C is connected in parallel to the furnace the voltage profile improves significantly though the harmonics present in the voltage spectrum are not reduced to a great extent.

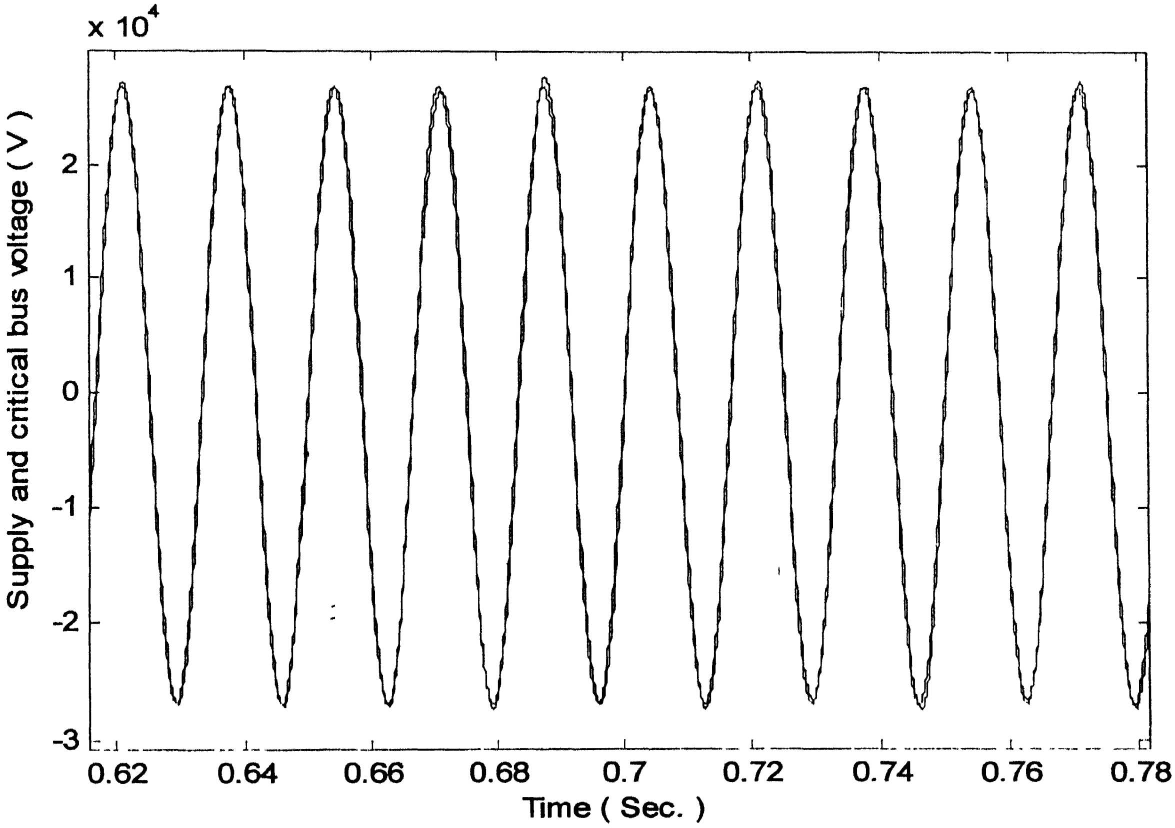


Figure 4.11 : Source and critical bus voltage waveforms

The figure 4.12 given below shows the variation in the r.m.s value of the voltage at the critical bus and the corresponding voltage spectrum at the critical bus with a S.V.C connected in shunt with the furnace is given in figure 4.13.

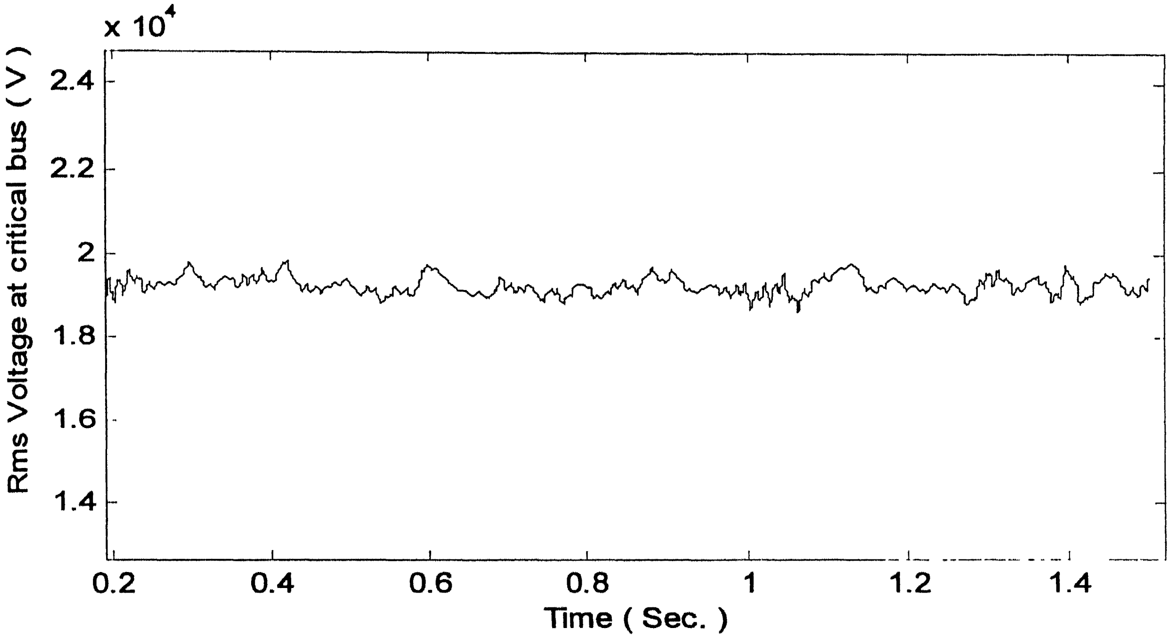


Figure 4.12 : r.m.s voltage at the critical bus

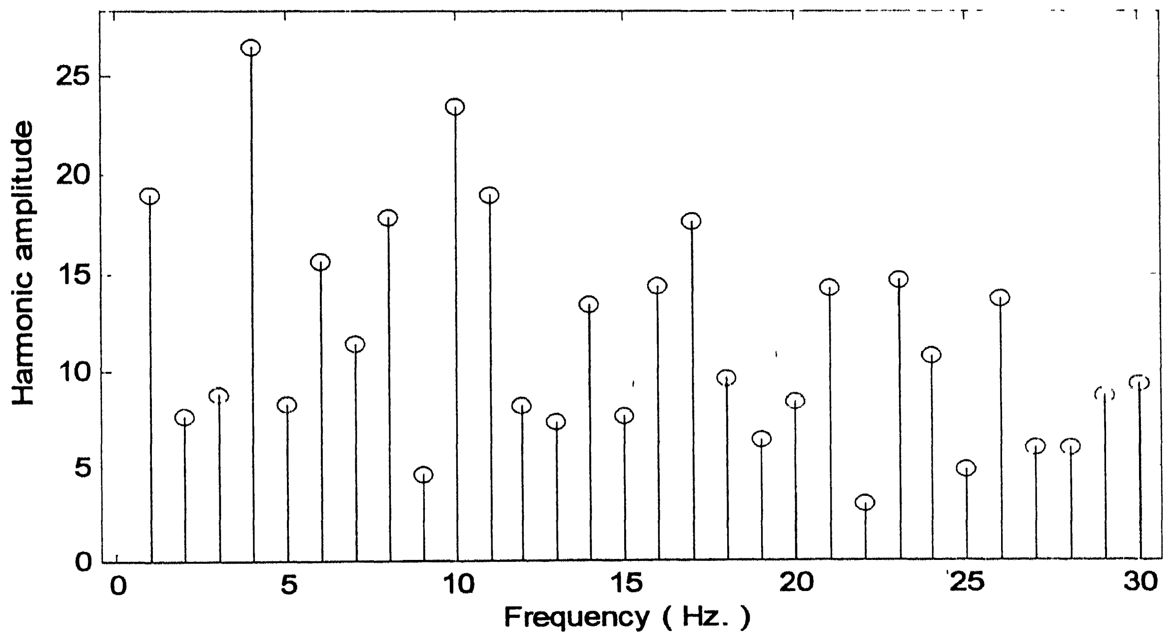


Figure 4.13 : Harmonic spectrum of the critical bus voltage

By comparing this figure with the corresponding figure in the previous chapter, it can be seen that we do have some improvement in the spectrum but not very significant and hence we can say that the flicker will not be reduced to a great extent as can be seen in the next section .

4.6.4 Flicker at the critical bus

Flicker is calculated at this bus in the same way as described in the previous chapter. As has already been seen from the previous figure that the voltage spectrum does contain quite a large amount of harmonics we do not expect a great improvement in the level of flicker at this bus.

Using the same definition of flicker level i.e. ΔV_{10} we achieve a flicker level

$$\Delta V_{10} = 50.12$$

Comparing this with the level obtained in the previous chapter we do see an improvement of around 15%, but it is limited primarily because of the slow speed of the S.V.C as compared to the fluctuations in the arc furnace parameters.

4.7 Conclusions

Having seen the operation of the arc furnace first without any compensation and then with a S.V.C connected in parallel we can conclude the following,

- The average reactive power required by the arc furnace can be compensated to a great extent by a S.V.C so that the load seems to be a resistive varying load if talked on an average basis.

- The source current though reduces in magnitude owing to the compensation of the fundamental part of the reactive current but still it has a lot of harmonics because of the discontinuous operation of the thyristor.
- The real power consumed by the load also shows large harmonics indicating the presence of large amount of real harmonic power which cannot be compensated with the help of a S.V.C and hence we ought to have a different method of compensating the reactive current which is fast and whose response is, ideally speaking instantaneous .

Chapter 5

THEORY OF INSTANTANEOUS COMPENSATION

5.1 Introduction

For single phase power systems with sinusoidal voltages and currents, quantities such as active power, reactive power, active current, reactive current, power factor etc. are based on the average concept.

Many authors have attempted to redefine these quantities to deal with 3 phase systems with unbalanced and distorted currents. Among them Akagi *et. al* [1] have introduced an interesting concept of instantaneous active and reactive power. This method provides an effective means to compensate for the instantaneous components of reactive power for 3 phase systems, but the theory does not work properly in the presence of zero sequence components as pointed out in [10]. As the arc furnace does contain zero sequence currents, we have for the purpose of this study used the theory proposed by Lai [10], which is explained in the next section.

5.2 Instantaneous real and reactive powers

For three phase systems, both the currents and voltages can be treated as vectors with 3 components one for each phase v.i.z.

$$\vec{i} = \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} \quad ; \quad \vec{v} = \begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} \tag{5.1}$$

where , i_a, i_b, i_c are the instantaneous values of phase currents .

v_a, v_b, v_c are the instantaneous values of phase voltages .

Now the theory proposed by Lai defines the instantaneous real and reactive powers as follows

$$p = \vec{v} \cdot \vec{i} \quad ; \quad q = \|\vec{q}\| = \|(\vec{v} \times \vec{i})\| \tag{5.2}$$

Applying simple vector algebra rules we have

$$p = v_a \cdot i_a + v_b \cdot i_b + v_c \cdot i_c \tag{5.3}$$

$$q = \left(q_a^2 + q_b^2 + q_c^2\right)^{1/2} \tag{5.4}$$

where,

$$q_a = \begin{vmatrix} v_b & v_c \\ i_b & i_c \end{vmatrix} \quad ; \quad q_b = \begin{vmatrix} v_c & v_a \\ i_c & i_a \end{vmatrix} \quad ; \quad q_c = \begin{vmatrix} v_a & v_b \\ i_a & i_b \end{vmatrix}$$

Taking these as the fundamental definitions it can easily be shown that the instantaneous current vector can be decomposed into two parts one being the instantaneous active component and the other being the instantaneous reactive component as follows

$$\vec{i} = \vec{i}_p + \vec{i}_q \tag{5.5}$$

where ,

$$\vec{i}_p = \left(\frac{p}{\vec{v}\cdot\vec{v}}\right)\vec{v} \quad ; \quad \vec{i}_q = \frac{\vec{q}\times\vec{v}}{(\vec{v}\cdot\vec{v})} \tag{5.6}$$

it can also be shown that

$$s = v \cdot i \quad ; \quad \lambda = \frac{p}{s} \tag{5.7}$$

where,

$$\vec{i}_p = \begin{pmatrix} i_{ap} \\ i_{bp} \\ i_{cp} \end{pmatrix} \quad ; \quad \vec{i}_q = \begin{pmatrix} i_{aq} \\ i_{bq} \\ i_{cq} \end{pmatrix}$$

$$v = \|\vec{v}\| \quad \text{and} \quad i = \|\vec{i}\|$$

s = instantaneous apparent power .

λ = instantaneous power factor .

Thus it can be argued that the load can be compensated if we can somehow compensate the reactive part of the current drawn by the load.

It turns out that the proposed theory works well in the case of balanced voltages but not in case of unbalanced voltages which is precisely the case with the arc furnace. To overcome this problem we consider the scheme proposed by Watanabae [13].

The active and reactive power consumed by the load in general varies about some mean value and hence both of them can be decomposed into their respective mean and oscillating components i.e.

$$p = \overline{p} + \widetilde{p} \quad ; \quad q = \overline{q} + \widetilde{q} \qquad 5.8$$

where,

$\overline{p}, \overline{q}$ are the average values of the instantaneous real and reactive power respectively.

$\widetilde{p}, \widetilde{q}$ are the oscillating components of the same .

The concept of instantaneous compensation involves that the source should supply only the average real power and everything else should be compensated for as depicted in the figure 5.1 given below.

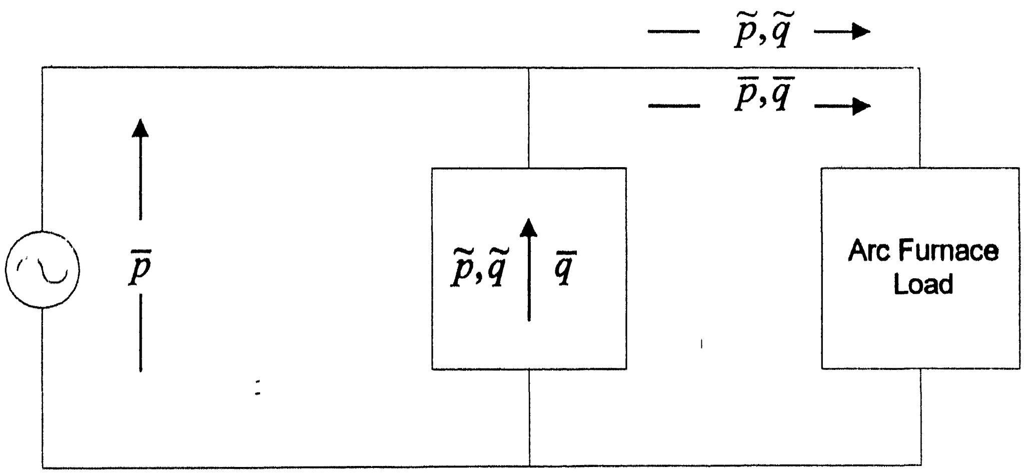


Figure 5.1 : Process of compensation of different power components

As is obvious from the definitions, these power components cannot be achieved directly. The process of evaluating them is being given in the next section.

5.3 Moving average technique

In order to estimate the average and alternating components of the real and reactive powers we either have to use a low pass filter or consider a moving window that considers only the latest values of the parameters. The second method has been employed for the study as it is faster and moreover does not effect the compensation characteristics because of instantaneous response unlike other low pass filters.

The averaging of p and q is performed over a period of one half cycle of the supply voltage as both p and q have fundamental components at twice the supply frequency. The moving window considered has the latest sampled data of instantaneous real and reactive powers for the last half cycle. These data are used to find the average of p and q i.e $\overline{p}\ \&\ \overline{q}$. Once we have the values of $\overline{p}\ \&\ \overline{q}$ we can subtract these from the instantaneous values of $p\ \&\ q$ respectively to obtain $\widetilde{p}\ \&\ \widetilde{q}$ .The process has been explained below.

Suppose we have N samples in the window and suppose the parameters for the n^{th} sampling instant are being evaluated then,

$$\overline{p} = \left\{ \left(\frac{1}{N} \right) \sum_{k=(n-N+1)}^{n} (p(k)) \right\} \qquad \text{whenever} \quad n \geq N. \tag{5.9}$$

$$\widetilde{p} = p - \overline{p} \tag{5.10}$$

As the time increments so does our moving window and so does the power components. Thus at any time we have all the power components derived from the data for the past half cycle and that is the best we could do.

The next section deals with the process of generating the required reference currents so that we may compensate the entire reactive and the harmonic real power.

5.4 Reference current generation

Suppose that the voltage vector at the point of compensation is given by $\vec{v}_l$ and the load current to be compensated is given by $\vec{i}_l$ then as pointed out earlier.

$$p_l = \vec{v}_l \cdot \vec{i}_l \qquad \text{and} \qquad \vec{q}_l = \vec{v}_l \times \vec{i}_l$$

further,

$$\vec{i}_{ql} = \frac{\vec{q}_l \times \vec{v}_l}{(\vec{v}_l \cdot \vec{v}_l)} = \frac{(\vec{v}_l \times \vec{i}_l) \times \vec{v}_l}{(\vec{v}_l \cdot \vec{v}_l)} \qquad 5.11$$

On simplification we have,

$$\vec{i}_{ql} = \vec{i}_l - \frac{p_l}{(\vec{v}_l \cdot \vec{v}_l)} \vec{v}_l \qquad 5.12$$

According to Lai if we can compensate this current we will have a virtually balanced 3phase load thus,

$$\vec{i}_{ref} = \vec{i}_l - \frac{p_l}{(\vec{v}_l \cdot \vec{v}_l)} \vec{v}_l \qquad 5.13$$

but as the arc furnace is typically one of the worst kind of loads the system is being subjected to and as has been shown earlier , the reactive as well as the real power being consumed varies wildly , the above mentioned theory , does not give very good result basically because the method relies on compensating the reactive current term and hence the arc furnace continues to taking the rapidly oscillating real power from the supply thus containing harmonics in the supply current .

Now we compensate for the harmonic real power by appropriately modifying the value of reference current required as follows

$$\vec{i}_{ref} = \frac{\vec{q}_l \times \vec{v}}{\vec{v}_l \cdot \vec{v}_l} + \frac{(\tilde{p}_l)}{\vec{v}_l \cdot \vec{v}_l}\vec{v}_l \qquad 5.14$$

where $\tilde{p}_l$ is the alternating component of the load real power .

Thus now the source has to supply only the average real power and hence we have a considerably better compensating scheme although it has some problems due to the random nature of the arc current but still this scheme turns out to be far better than the methods used presently for the purpose of arc furnace compensation .

On simplification the above expression becomes

$$\vec{i}_{ref} = \vec{i}_l - \frac{\overline{p}_l}{\vec{v}_l \cdot \vec{v}_l}\vec{v}_l \qquad 5.15$$

where,

$\overline{p}_l$ is the average value of the load real power and is equal to $p_l - \tilde{p}_l$ and is calculated by the moving average method as explained earlier.

Now if we can somehow track this reference current, the entire reactive and the harmonic real power will be compensated. Although this does not guarantee perfect compensation because the reference current has been generated with the help of data for the last half cycle and the furnace parameters may vary at the time of compensation.

5.5 Conclusions

Thus it can be concluded that the load currents and powers can be decomposed into their respective average and oscillating components namely,

$$\overline{p}_l, \widetilde{p}_l \qquad \& \qquad \overline{q}_l, \widetilde{q}_l$$

It can be said that $\widetilde{p}_l$ & $\widetilde{q}_l$ contribute towards the current harmonics present in the supply current . In normal cases the contribution of $\widetilde{q}_l$ is far greater than that of $\widetilde{p}_l$ and hence theory proposed by Lai works very well but in the case of arc furnace $\widetilde{p}_l$ is far greater than that for other equivalent loads and hence it is absolutely essential to compensate for q_l as well as $\widetilde{p}_l$.

The implementation of this theory now involves that these reference currents be continuously tracked and compensated for with the help of suitable current source and control scheme such as bang-bang hysteresis control.

Chapter 6

COMPENSATION WITH A CURRENT SOURCE

6.1 Introduction

Several different S.V.C configurations are presently used for compensation of arc furnaces. All the conventional S.V.C's employ thyristors to vary the effective value of passive reactive elements connected in parallel with the load. The design of these S.V.C's is such that the compensation of the load occurs discontinuously in steps of one half cycle or more of the power line frequency. Conceptually S.V.C's are intended to compensate only the fundamental reactive current of the arc furnace and hence the latter continues to take the harmonic real and reactive powers from the source, which is the main cause of flicker.

Tuned filters are also used in conjunction with the S.V.C's if harmonics in the load current are high .The inherent delay of these S.V.C's may be too great for compensation

of loads such as arc furnace where the behavior of the arc is a random phenomena. It has already been justified in the previous chapters that the conventional methods of compensating the arc furnace with the help of S.V.C's falls short of the requirements necessary for flicker management. This is primarily because of the fact that the arc current changes rapidly and so does the required compensating current. Thus it reasonable to investigate the compensation effects based on the theory proposed in the previous chapter, by using inverters as current sources to compensate the arc furnaces instantaneously.

This chapter deals with compensation of arc furnace system instantaneously with the help of current sources. The current required for compensation is derived instantaneously and the current source tracks this reference current in order to accomplish compensation. This method has some distinct advantages over the conventional methods using the S.V.C's such as,

- The response is very fast compared to conventional methods.
- Not only the fundamental but also the harmonic reactive currents can be compensated.
- By properly generating the reference currents we can also compensate the harmonic real power so that the arc furnace virtually behaves as a balanced resistive load.

The first part of this chapter deals with compensation of arc furnace with an ideal current source and the second part deals with compensation with the help of a current source realized with a 3phase 2level inverter.

6.2 System configuration and state equations

The system considered for compensation is again the same with the only difference that now we have a current source in parallel with the furnace as shown in the figure 6.1,

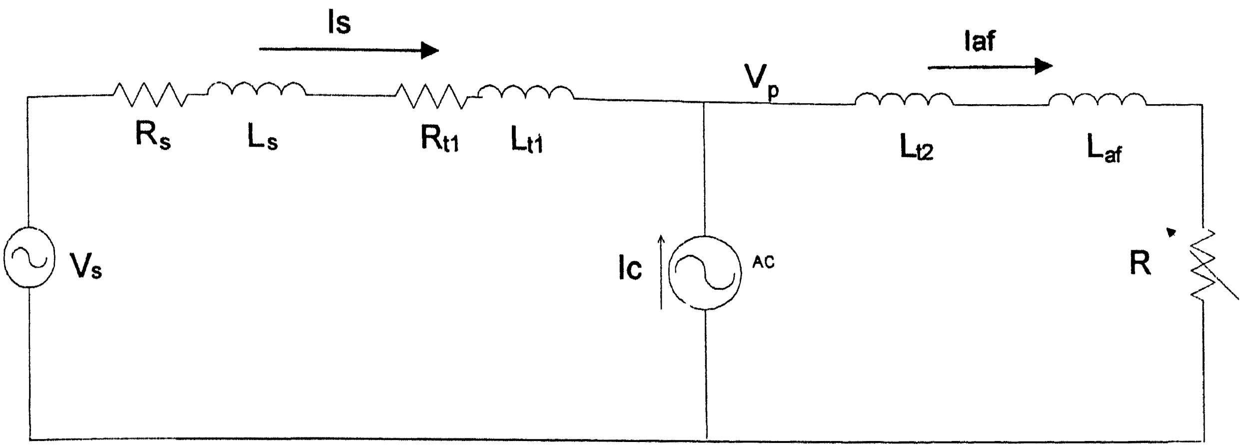


Figure 6.1 : Single phase equivalent of the arc furnace system

In the above figure I_c is the current supplied by the compensator and follows a generated reference current as explained in the next section.

The equations governing the arc furnace system shown above are,

$$V_s = (R_s + R_{t1}) \cdot I_s + (L_s + L_{t1}) \cdot \frac{dI_s}{dt} + V_p \qquad 6.1$$

$$V_p = (R_{t2} + R) \cdot I_{af} + (L_{t2} + L_{af}) \cdot \frac{dI_{af}}{dt} \qquad 6.2$$

$$I_{af} = I_s + I_c \qquad 6.3$$

where,

I_c is the compensator current that follows the reference current I_{ref} which in turn is generated as explained in the previous chapter .

These set of differential equations are again converted to state equations of the type,

$$\dot{X} = AX + BU$$

and $\quad$ 6.4

$$Y = CX + DU$$

where,

$$X = \begin{pmatrix} I_s \\ I_c \end{pmatrix} \quad , \quad Y = \left(V_P\right) \quad , \quad U = \begin{pmatrix} V_s \\ F_c \end{pmatrix}$$

In the above expression F_c is a function that represents,

- The max. rate of change of current through the current source in case the compensator is assumed ideal.
- If the compensator is assumed to be of 3phase 2 level type, this represents the instantaneous voltage difference between the magnitude of the capacitor voltage and the compensator bus as explained in the following sections.

The matrices A, B, C, D are different for the case of ideal and 2 level inverter and are given in the respective sections.

6.3 Flow chart for the process of compensation

The flow chart for the process of compensation with an ideal current source is given in the following pages .The inverter logic, which is assumed ideal in the first case and in the second case 3phase 2level type, is explained in their respective sections .

The flow chart for various functions which have been called are also given in the subsequent pages.

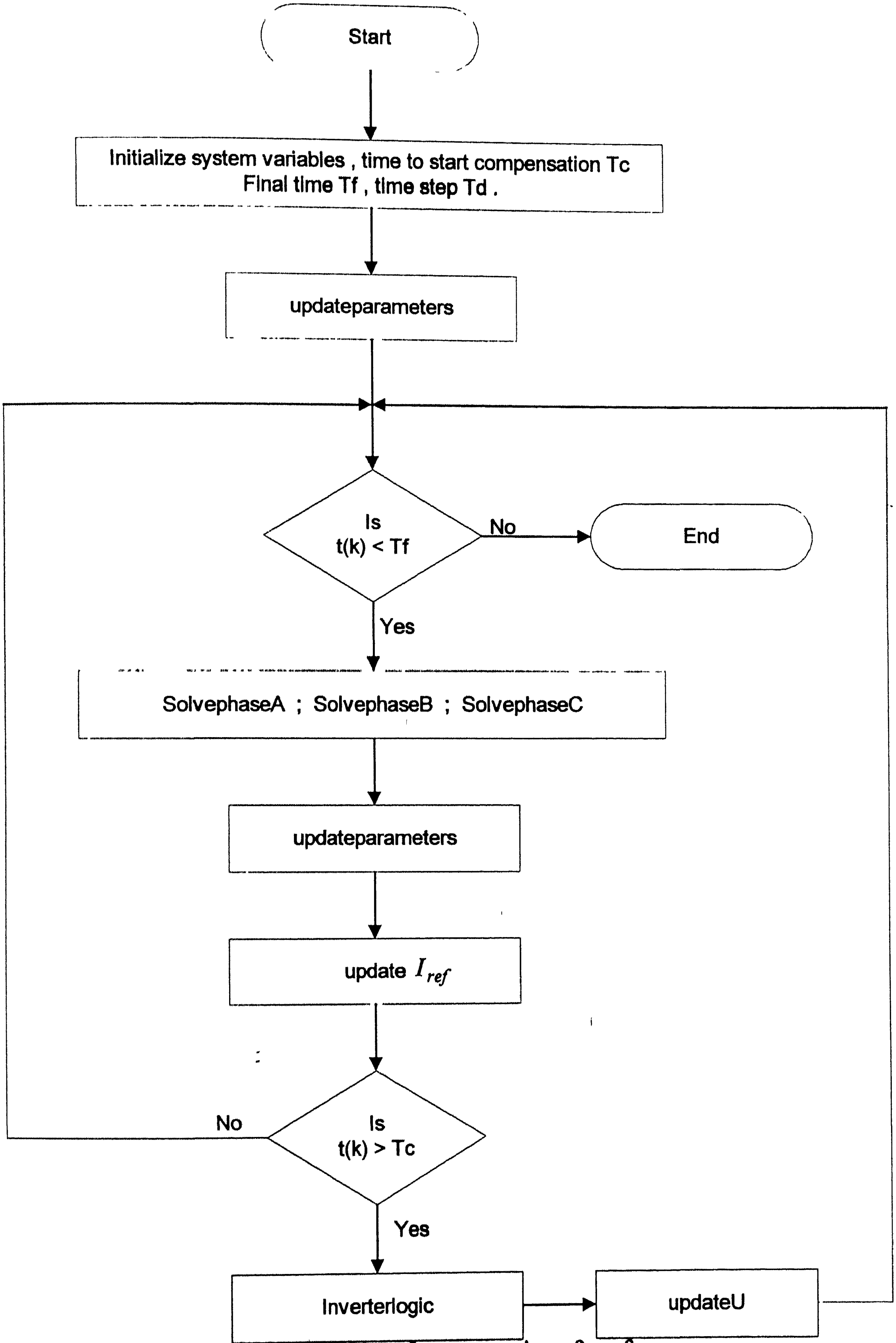


Figure 6.2 : Flow chart for the process of compensation of arc furnace

k = k + 1 ;

t(k) = t(k-1) + Td ;

$$V_s(1,k) = V_o \sin\left(w \cdot t(k)\right)$$

$$V_s(2,k) = V_o \sin\left(w \cdot t(k) - \frac{2\pi}{3}\right)$$

$$V_s(3,k) = V_o \sin\left(w \cdot t(k) + \frac{2\pi}{3}\right)$$

$$I_l(1,k) = X_a(1,k) + X_a(2,k)$$

$$I_l(2,k) = X_b(1,k) + X_b(2,k)$$

$$I_l(3,k) = X_c(1,k) + X_c(2,k)$$

solve

$$Y = CX + DU$$

and update Vp

$$p_l(k) = \vec{V}_p \cdot \vec{I}_l \qquad \vec{q}_l(k) = \vec{V}_p \times \vec{I}_l$$

$$p_s(k) = \vec{V}_s \cdot \vec{I}_s \qquad \vec{q}_s(k) = \vec{V}_s \times \vec{I}_s$$

Figure 6.3 : Flow chart for the function updateparameters

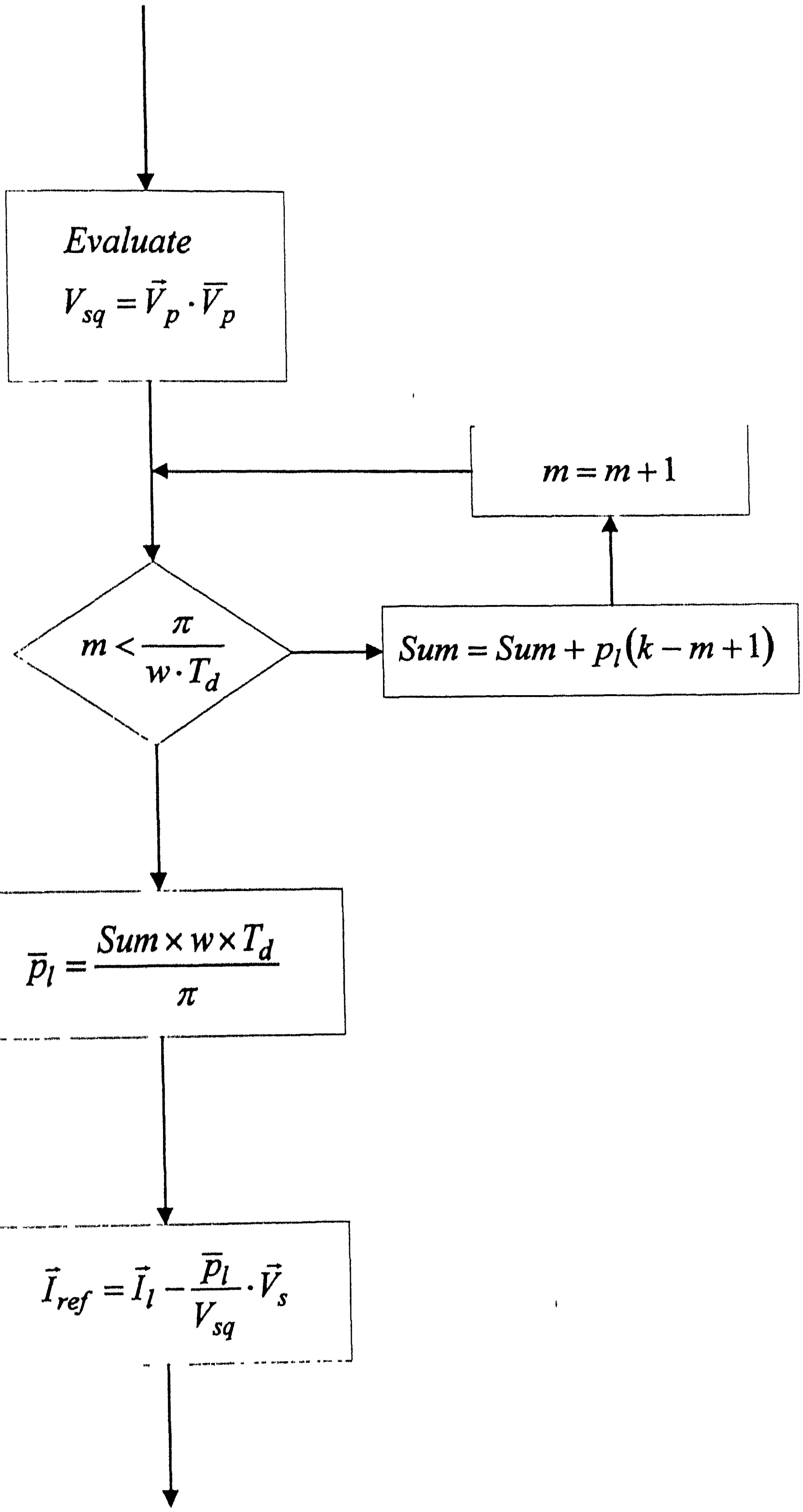


Figure 6.4 : Flow chart for the function update I_{ref}

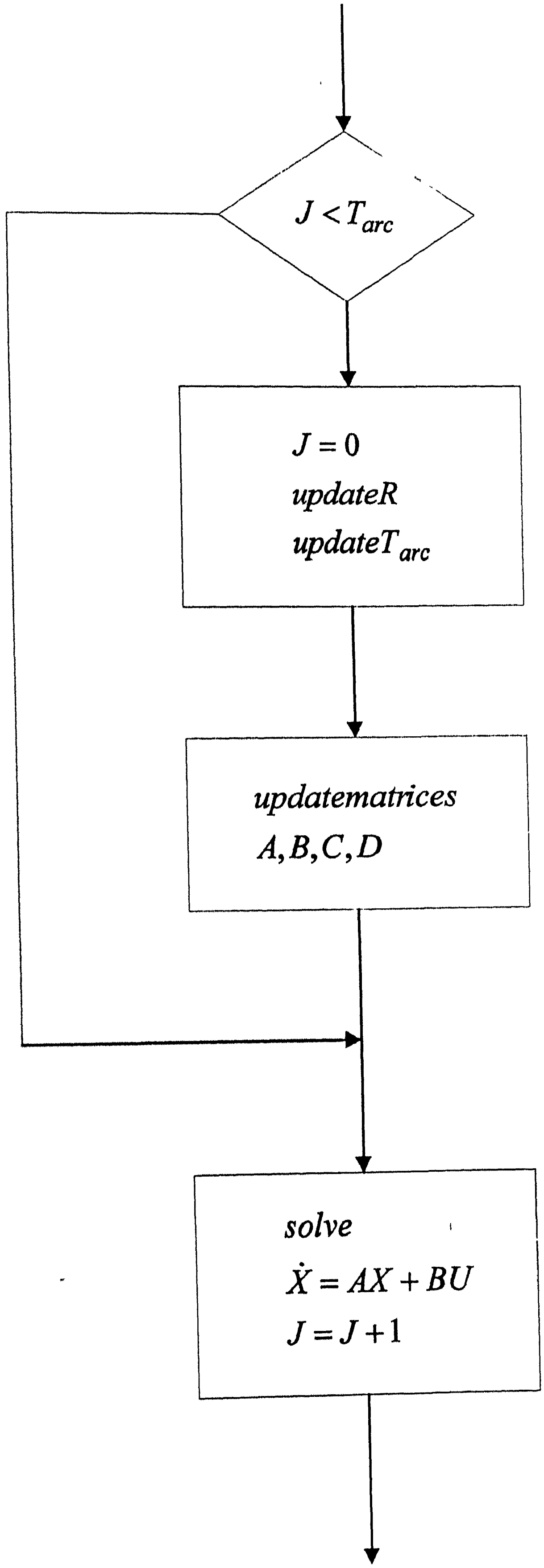


Figure 6.5 : Flow chart for the function Solvephase

6.4Compensation with an ideal current source

6.4.1 Introduction

The ideal current source used for the compensation of arc furnace is assumed to have a constant rate of change of current whose magnitude is decided by hysteresis band and the maximum switching frequency allowed for the invertèr to operate.

Ideally the current source should have an infinite band width but in our case as the compensator is attached to a bus where the voltages themselves are unbalanced and inductances are present on the either side of the compensator bus thus putting a limit on the maximum magnitude of the rate of change of current . Without this limit we will have sharp voltage spikes at the compensator bus tending to make the system unstable.

For the purpose of our study we have fixed the following parameters for the current source and the system as such,

- The rate of change of current through the current source has been fixed at 1kA per msec. .
- The hysteresis band has been fixed at $\pm 10A$ around the actual reference current.

Thus we can say that,

$$F_c = \frac{dI_c}{dt} = \pm 10^6 \qquad 6.5$$

For this case the matrices A, B, C, D are as follows,

$$A = \begin{pmatrix} -\dfrac{(R_s + R_{t1} + R_{t2} + R)}{(L_s + L_{t1} + L_{t2})} & -\dfrac{(R_{t2} + R)}{(L_s + L_{t1} + L_{t2})} \\ 0 & 0 \end{pmatrix}$$

$$B = \begin{pmatrix} \dfrac{1}{(L_s + L_{t1} + L_{t2})} & -\dfrac{L_{t2}}{(L_s + L_{t1} + L_{t2})} \\ 0 & 1 \end{pmatrix}$$

$$C = \left(-\{(R_s + R_{t1}) + (L_s + L_{t1}) \cdot A_{11}\} \quad -(L_s + L_{t1}) \cdot A_{12}\right)$$

$$D = \left(-\{(L_s + L_{t1}) \cdot B_{11} - 1\} \quad -(L_s + L_{t1}) \cdot B_{12}\right)$$

6.4.2 Reference current generation and inverter control

The system of equations is converted to discrete form and the required reference current is evaluated after each time step. In order to compensate for the entire reactive power and the alternating real power i.e. $(q \ \& \ \tilde{p})$ the reference current required is given by,

$$\vec{I}_{ref} = \vec{I}_{af} - \frac{\overline{p}_l}{\vec{V}_p \cdot \vec{V}_p} \vec{V}_p \qquad 6.6$$

where ,

$\overline{p}_l$ is the average real power taken by the load during the last half cycle .

Thus the control flow for the current source is as follows,

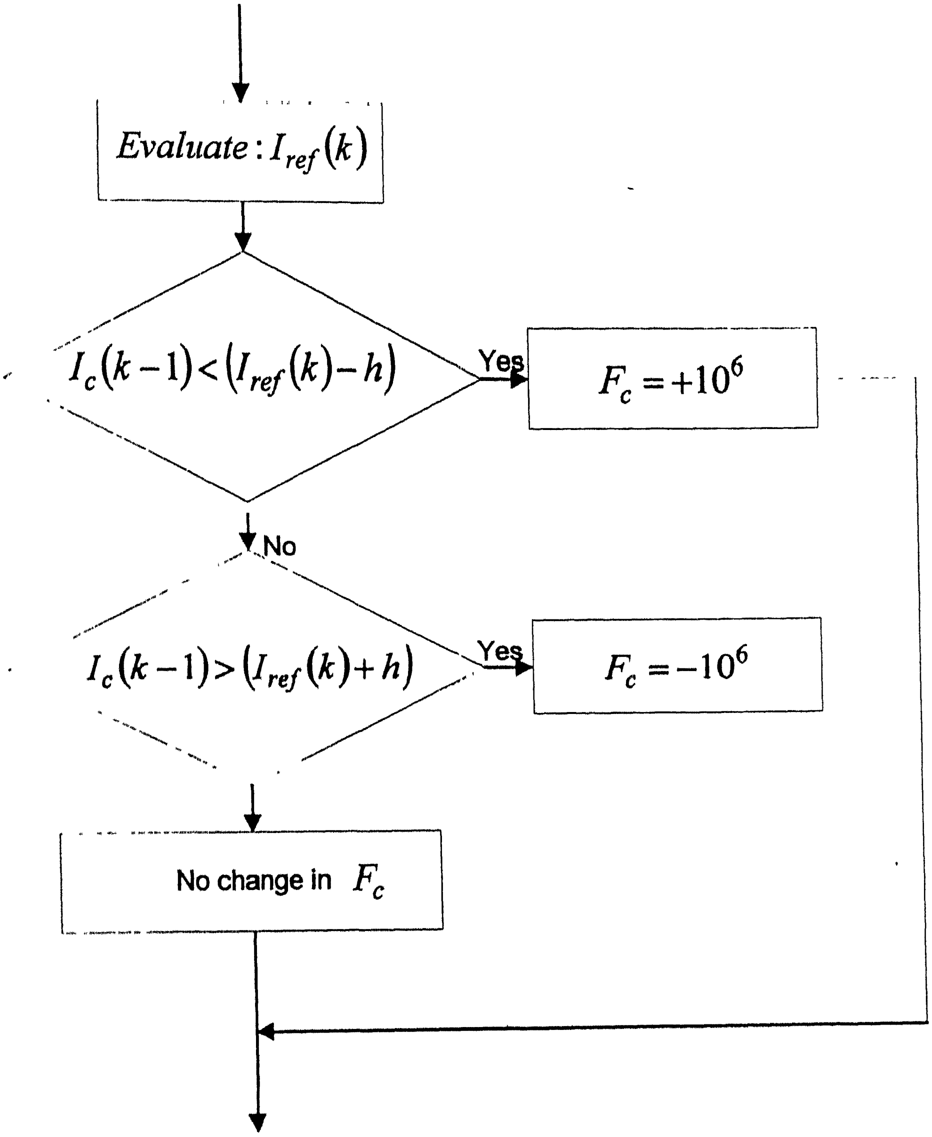


Figure 6.6 : Flow chart for the current source control

6.4.3 Arc current source current and their spectrum

It can be seen from the figures 6.7, 6.8 and 6.9 that we have a very significant improvement in the source current waveform and its harmonic content. The figures below show that there is a reduction in the r.m.s. current taken from the source because of the compensation of the entire reactive power.

The figures also indicate that the power factor has been improved to a value near unity , further , because of the compensation of harmonic real power the variations in the source current are reduced significantly .

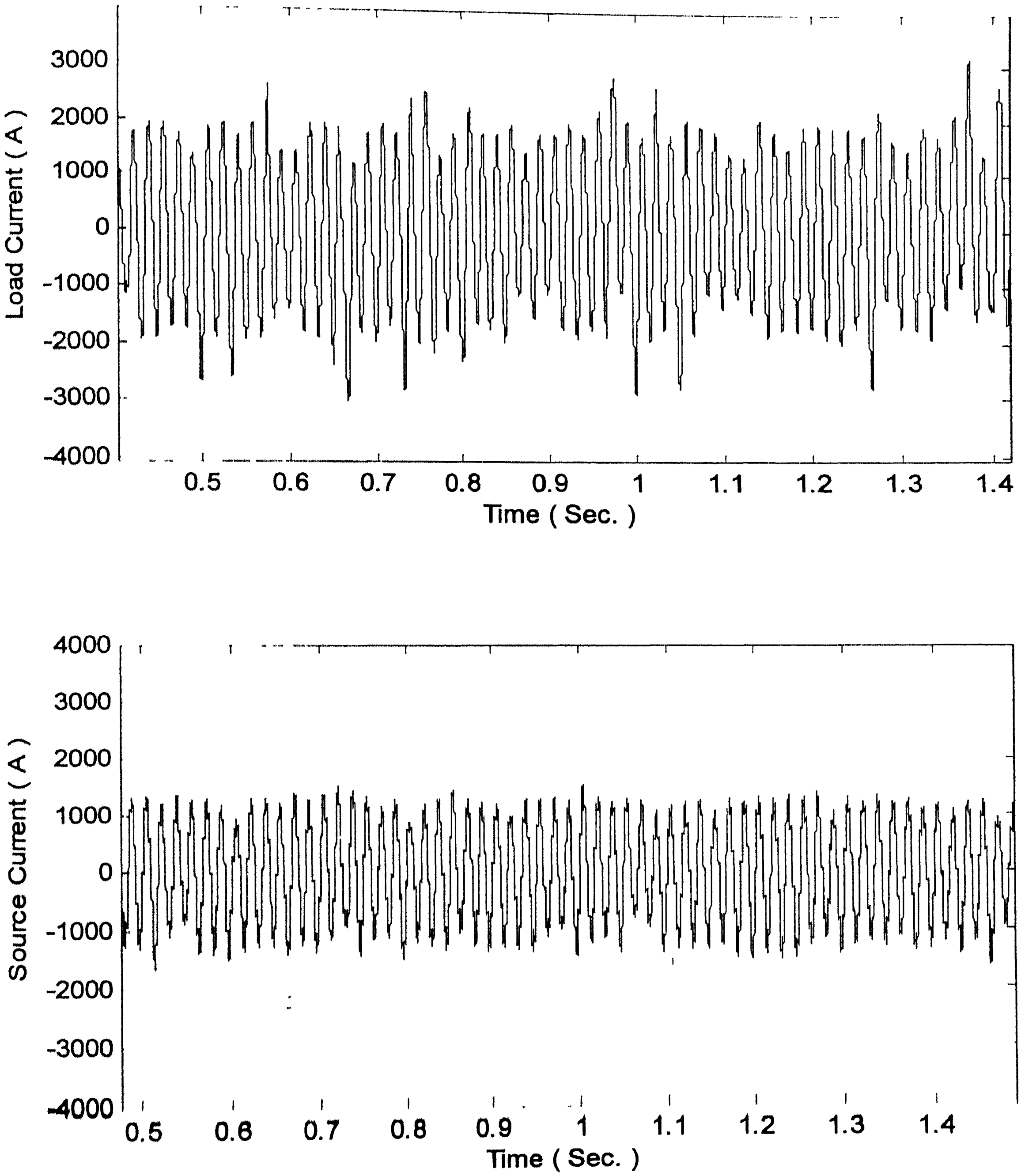


Figure 6.7 : Arc and supply current

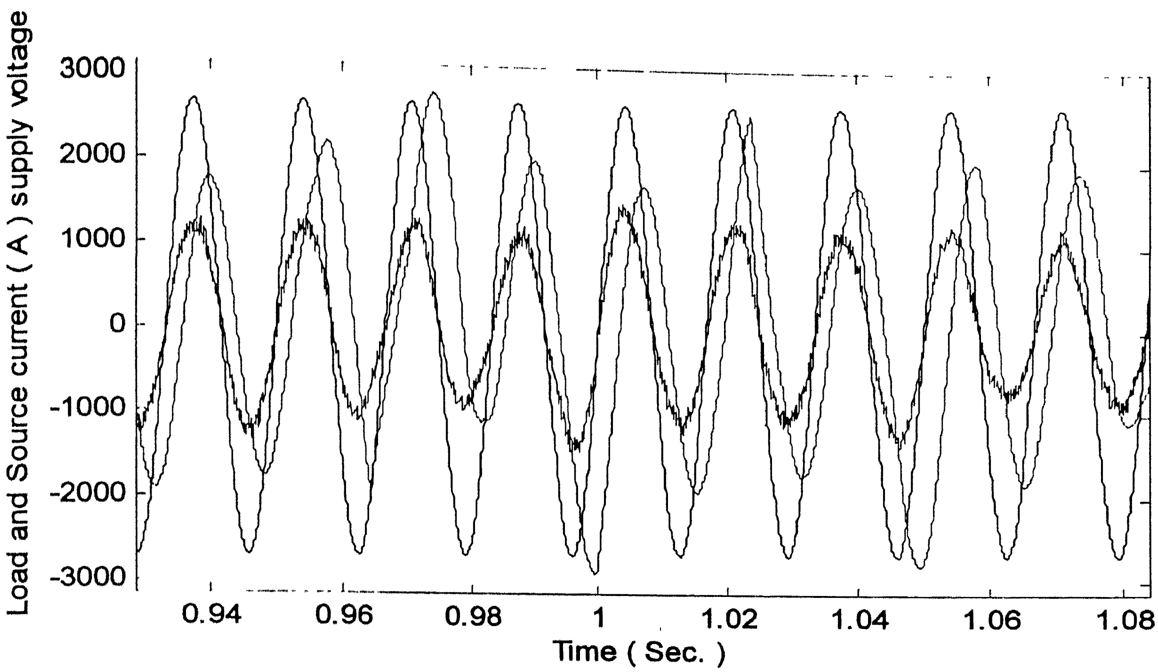


Figure 6.8 : Load and source current along with source voltage

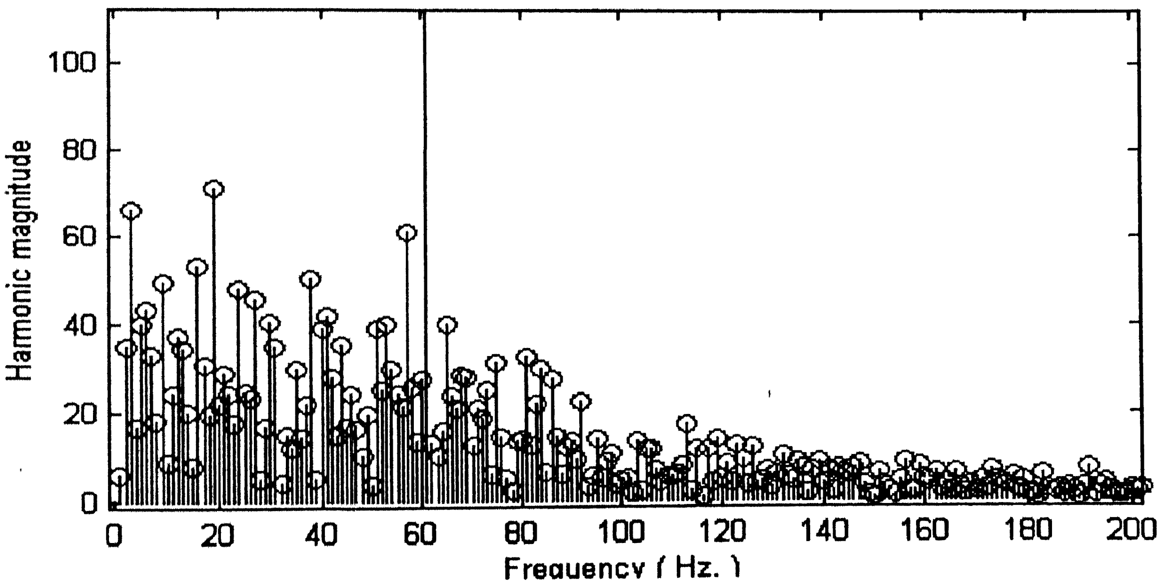


Figure 6.9a : Load current harmonic spectrum

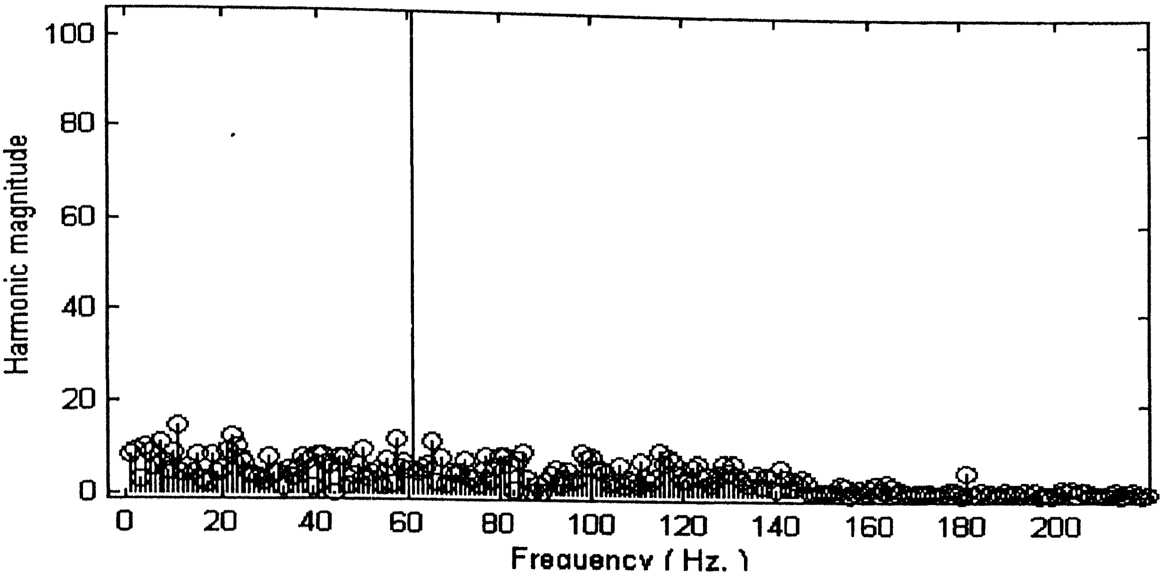


Figure 6.9b : Source current harmonic spectrum

6.4.4 Reference current and the compensator current

The reference current has been generated in such a way so as to compensate both the entire reactive power as well as harmonic real power. The figures 6.10 and 6.11 below shows the waveform of the required compensator current along with the actual compensator current that tracks the reference current within a band of 10A around the reference value .

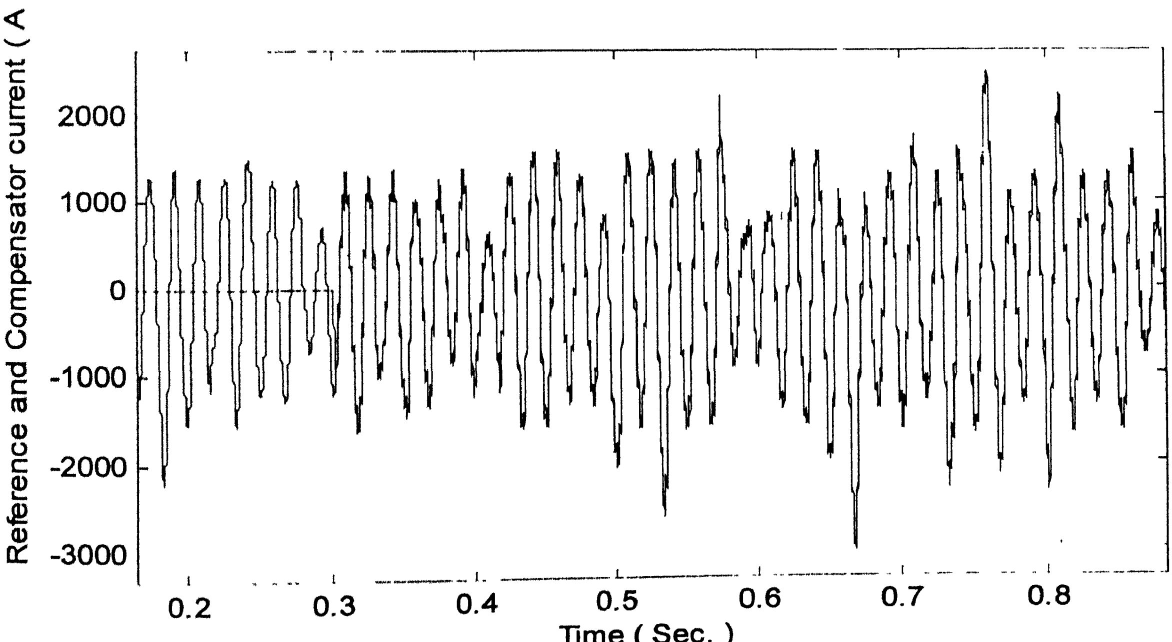


Figure 6.10 : Reference and compensator current

The figure below shows a blown up view of the compensator current tracking the reference current,

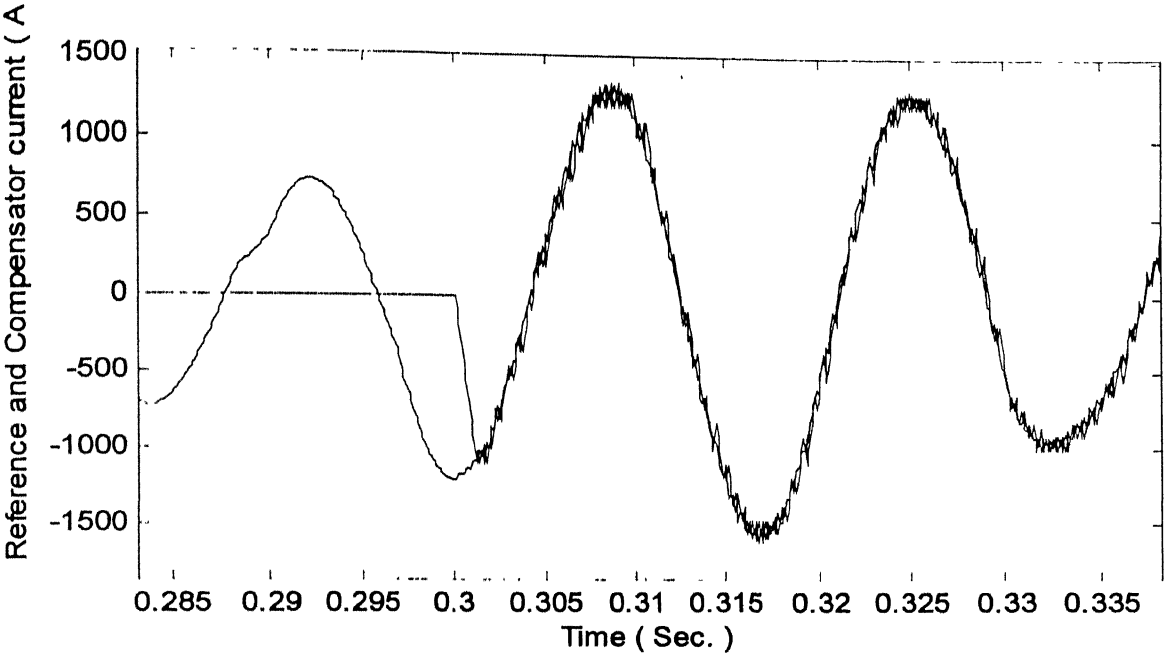


Figure 6.11 : Compensator current tracking the reference current

It can be seen from the figure above that infact the compensator does track the reference value within the specified band . The switching frequency of the compensator is variable with a maximum rate of 5kHz. Which is obtainable with the existing high power switching devices.

6.4.5 Real and reactive power

The figures 6.12 and 6.13 indicate the real and reactive power being consumed by the load and that being supplied by the source,

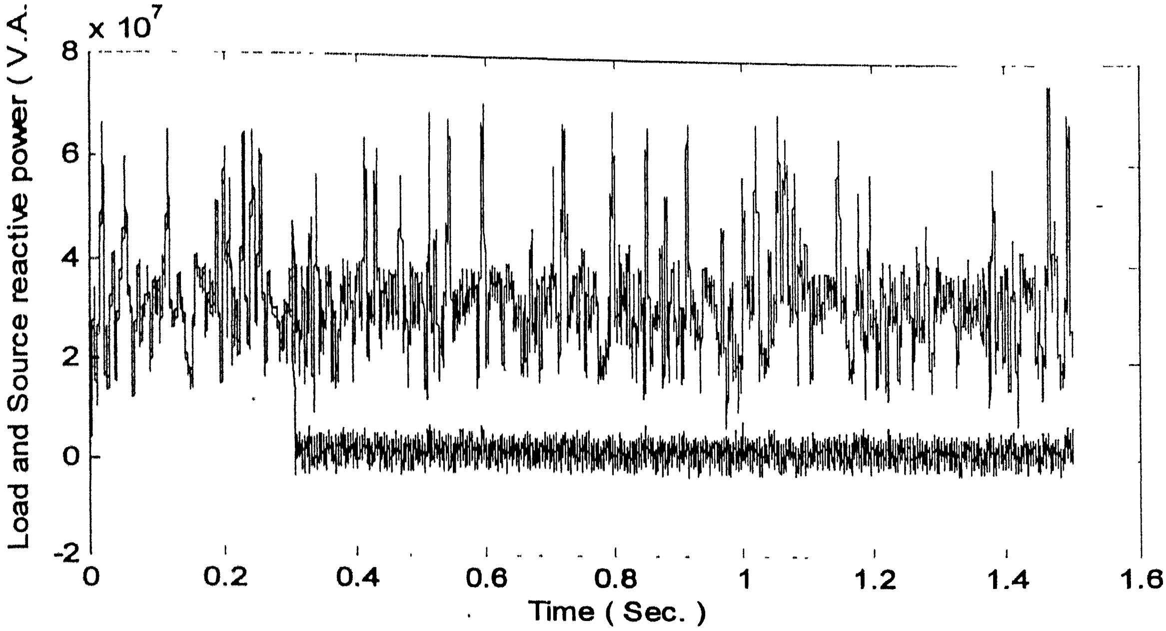


Figure 6.12 : Load and source reactive powers

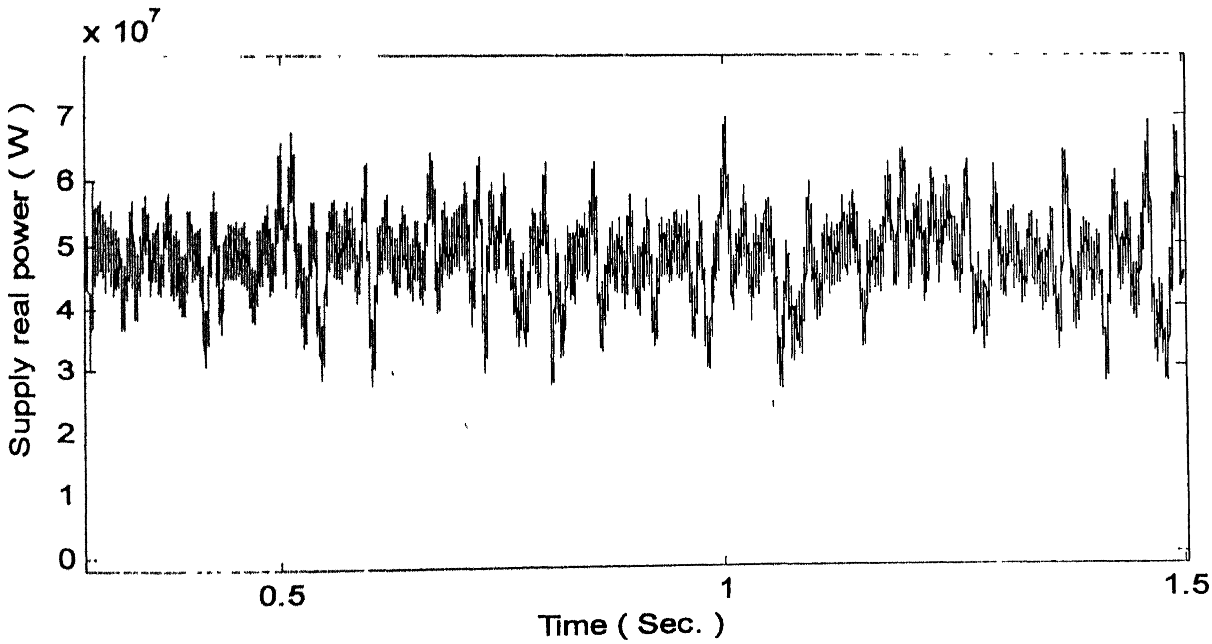


Figure 6.13a : Source real power

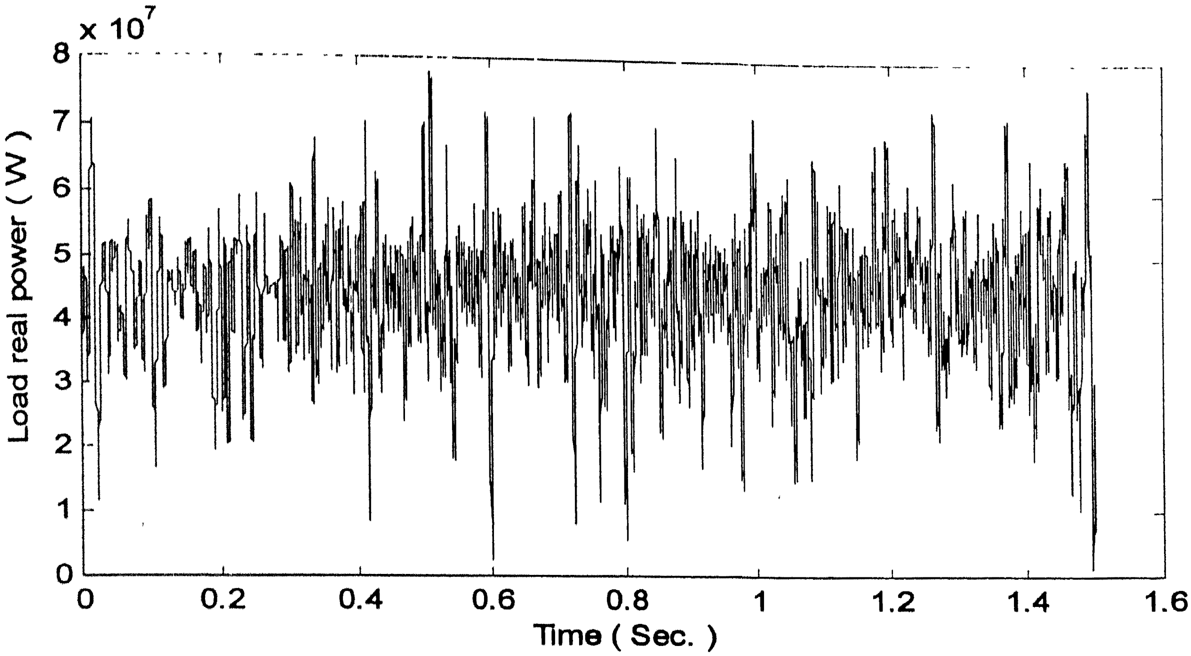


Figure 6.13b : Load real power

It is clear from the figures above that the compensated load behaves in a much better way than an uncompensated load because now the load draws negligible reactive power and less oscillating real power, thus achieving a very good compensation.

6.4.6 Voltage at the critical bus and flicker

The compensation has a boosting effect on the voltage at the critical bus. It will been shown below that instantaneous compensation not only improves the voltage profile but also reduces the harmonic content considerably.

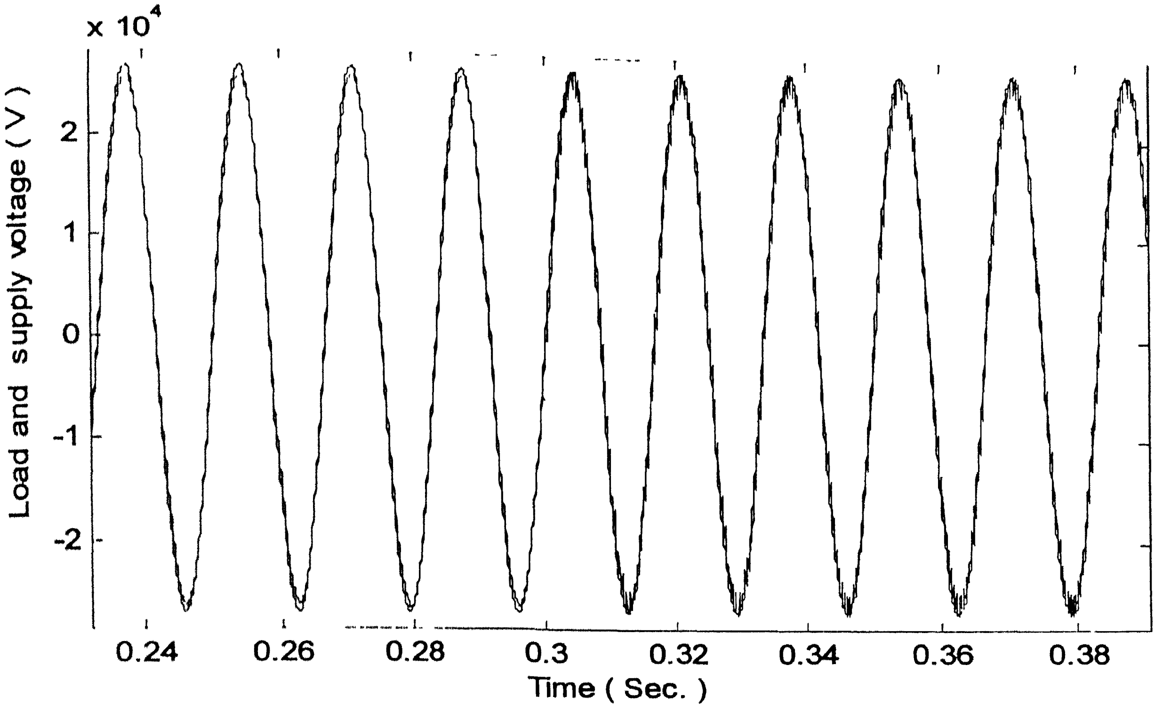


Figure 6.14 : Source and critical bus voltages

We can see from the figure 6.14 that just after the compensation begins there is a improvement in the voltage profile at the critical bus. Although we have some high frequency harmonics in the waveform but they are generally not severe on the system.

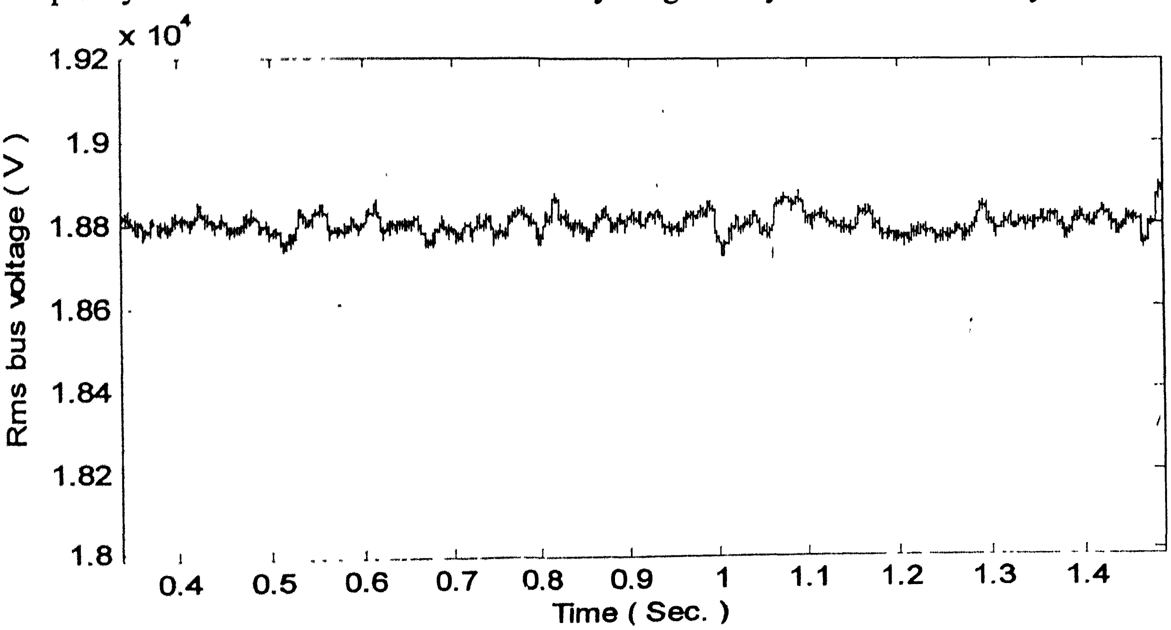


Figure 6.15 : r.m.s. voltage at the critical bus

Comparing this figure with the corresponding figure in chapter 3 we can see that the rms value has increased to within $\pm 1\%$ of the average rms which has increased to around 98.5 % of the supply rms value.

Figure 6.16 shows the harmonic content of the critical bus voltage,

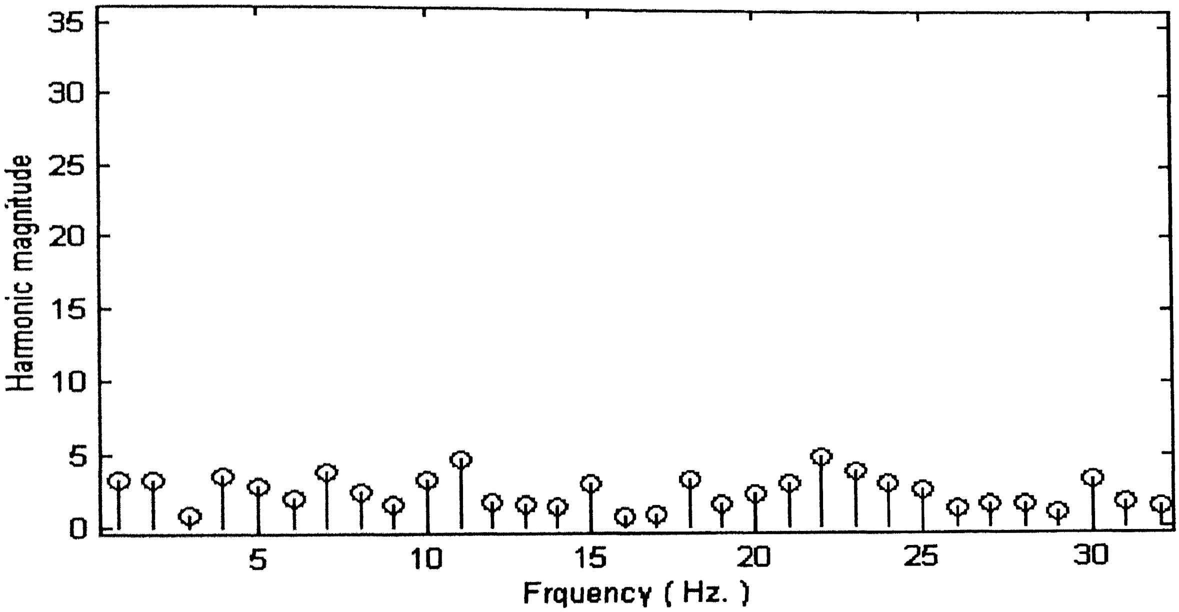


Figure 6.16 : Harmonic spectrum of critical bus voltage

Comparing this figure with the corresponding figure in chapter 3 we can see the tremendous improvement in the harmonic content.

The level of flicker (ΔV_{10}) in this case turns out to be,

$$\Delta V_{10} = 10.8$$

This value is substantially lower than that in the previous chapter and shows the dramatic improved of around 83% achieved with instantaneous compensation.

6.5 Compensation with a current controlled 3phase 2level Inverter

6.5.1 Introduction

In this section we will simulate a 2level 3phase inverter and control it to act as a current source which will be made to track the reference current for compensation of the load. The circuit diagram for the inverter is given below ,

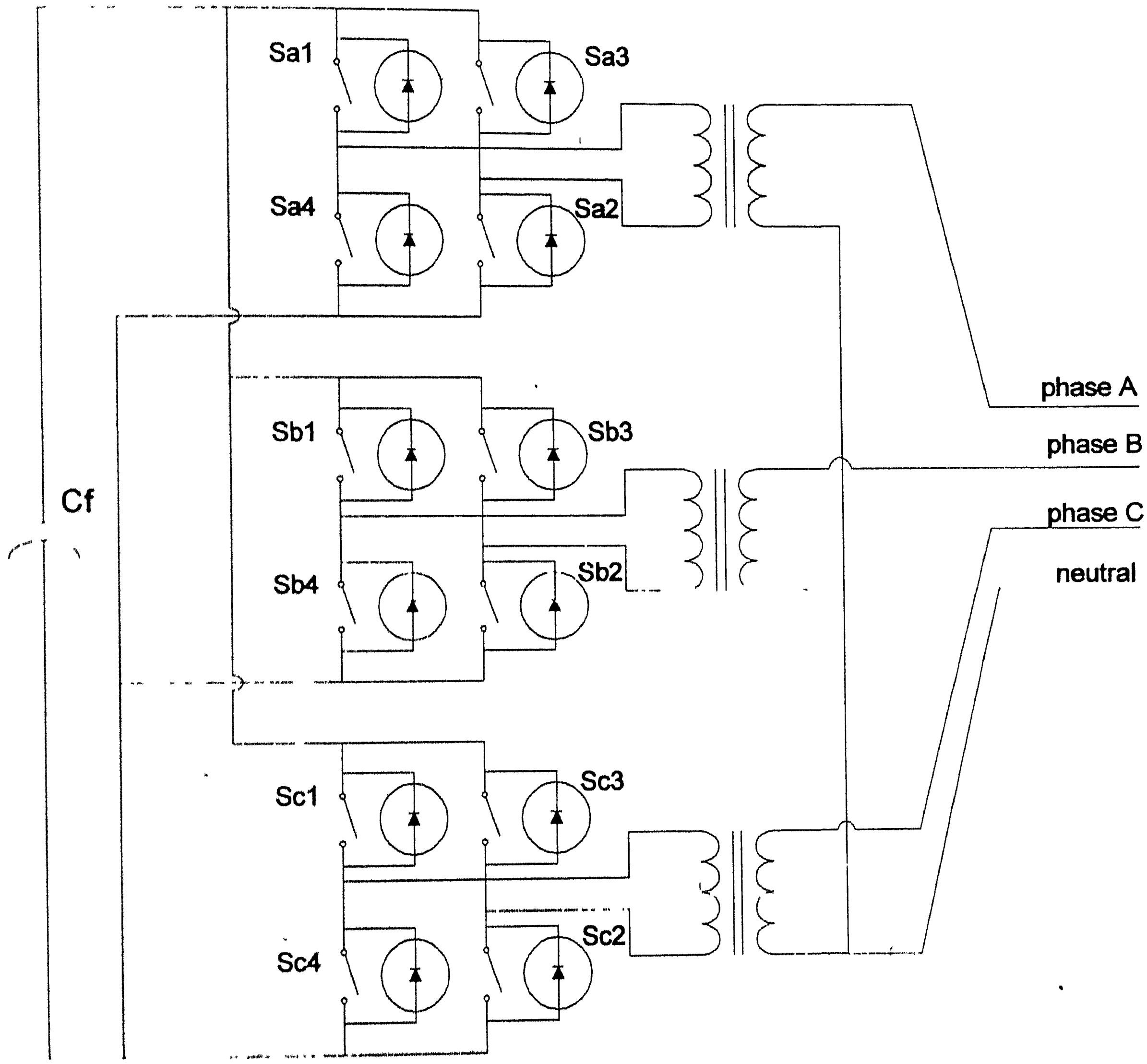


Figure 6.17 : 2level 3phase inverter configuration

We have three independent single phase bridge inverters with four switches in each. The switches are used in pairs to control the current through the inverter as follows,

Switches 1 & 2 are operated simultaneously for any phase if we are required to increase the current through that phase of the compensator and the switches 3 & 4 are operated simultaneously if we are required to decrease the current through a particular phase of the compensator.

The switching logic is dictated by the reference current being generated after each time step . If the compensator current is less than the lower value of the hysteresis band we turn on switches 1 & 2 and if the current is more than the upper value of the hysteresis band we turn on switches 3 & 4 . This logic is evaluated after each time step thus compensating the load instantaneously.

The capacitor in the inverter will discharge if we do not its voltage , hence in order to maintain its voltage we have a control loop which generates a loss signal which is proportional to the voltage difference between the reference value of the capacitor voltage and the actual capacitor voltage . This signal is incorporated in the reference current generation algorithm so as to draw the requisite amount of real power from the source and thus maintain the capacitor voltage. The control flow for the process is given in the next section.

6.5.2 Reference current generation and inverter control

The reference current required to compensate the arc furnace is generated by the algorithm stated in chapter5. When compensating with a non ideal inverter we have to take into consideration the losses associated with the inverter or else the capacitor may be drained of charge.

The inverter can be modeled as a capacitor connected in series with a resistance and an interfacing inductance that limits the rate of rise or decay of current through the inverter thus checking discharging of the capacitor.

The single phase equivalent for the inverter configuration is shown in figure 6.18,

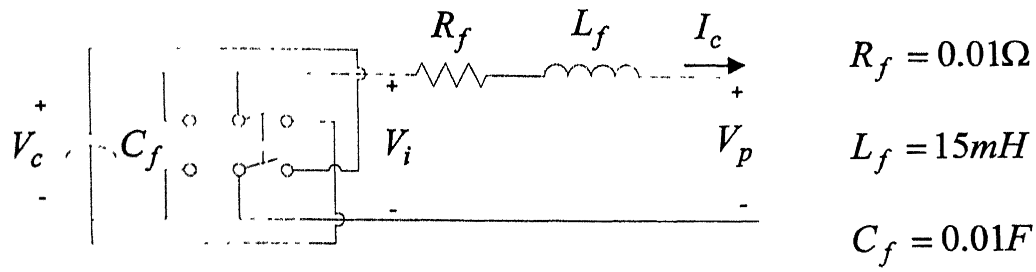


Figure 6.18 : Single phase equivalent of the inverter configuration

The differential equations governing the inverter is as follows,

$$V_{ia} = R_f \cdot I_{ca} + L_f \cdot \frac{dI_{ca}}{dt} + V_{pa} \qquad 6.7.1$$

$$V_{ib} = R_f \cdot I_{cb} + L_f \cdot \frac{dI_{cb}}{dt} + V_{pb} \qquad 6.7.2$$

$$V_{ic} = R_f \cdot I_{cc} + L_f \cdot \frac{dI_{cc}}{dt} + V_{pc} \qquad 6.7.3$$

$$I_{ct} = -C_f \cdot \frac{dV_c}{dt} \qquad 6.8$$

where,

V_{ia}, V_{ib}, V_{ic} are the inverter terminal voltages and can be either $+V_c or -V_c$ depending upon the switching state at that instant.

I_{ca}, I_{cb}, I_{cc} are the inverter phase currents and $I_{ct} = I_{ca} + I_{cb} + I_{cc}$.

V_{pa}, V_{pb}, V_{pc} are the phase voltages at the critical bus.

A loss signal representing the error in the capacitor voltage with respect to the reference voltage is generated and fed to a proportional controller. The output of the controller, P_{loss} , is used to update the required reference current as follows ,

$$\vec{I}_{ref} = \vec{I}_l - \frac{(\overline{p} + P_{loss})}{\vec{V}_p \cdot \vec{V}_p} \cdot \vec{V}_p \qquad 6.9$$

where,
$$P_{loss} = K_p (V_{ref} - V_c) \qquad 6.10$$

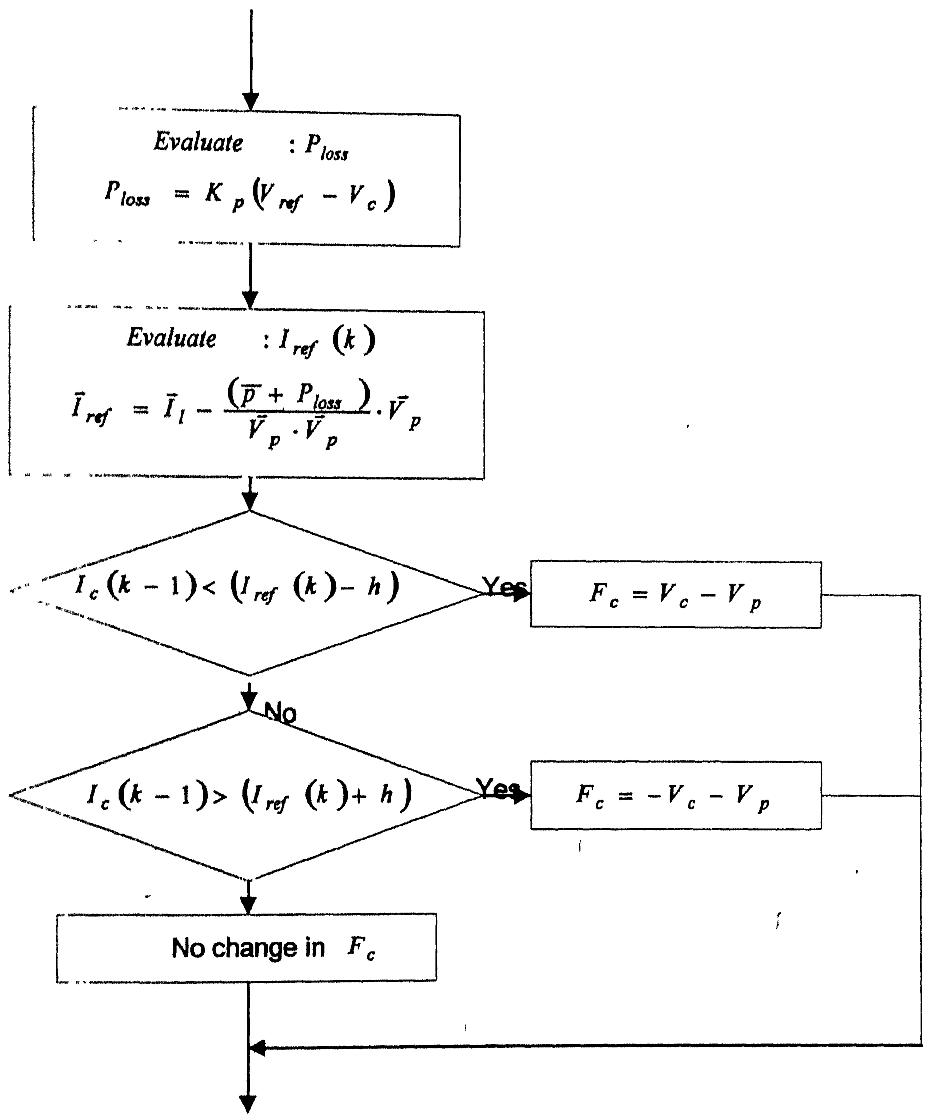
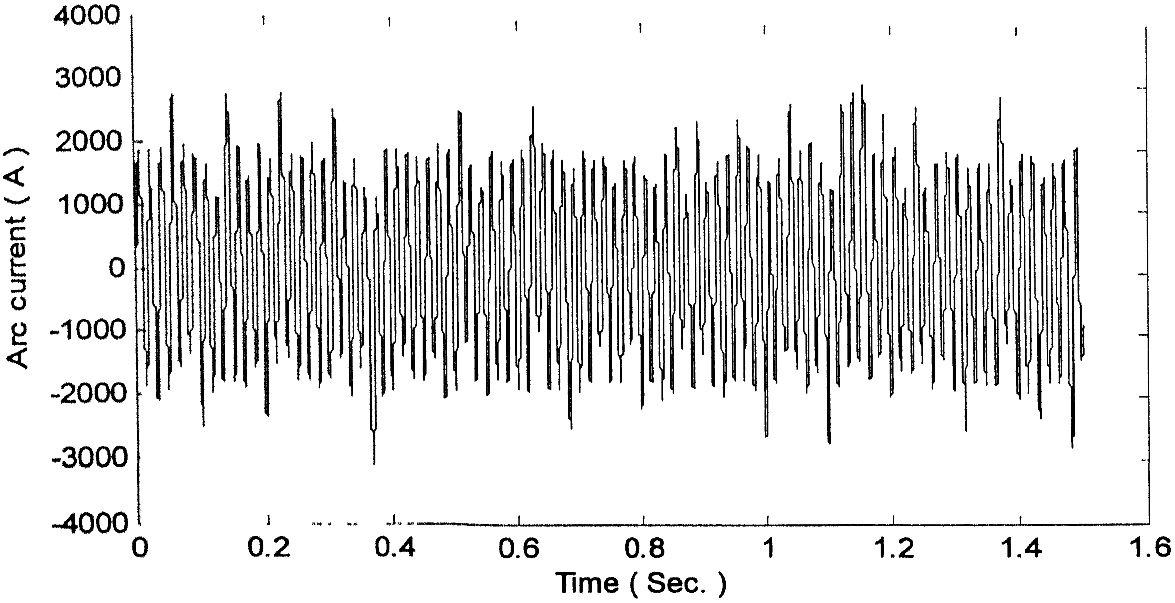


Figure 6.19 : Flow chart for the control of inverter

6.5.3 Arc & source current and their spectrum

The figure 6.20 show the load and the source current waveforms . It can be seen from the figures that there is a significant improvement in the waveform of the source current as compared to the load current .The random fluctuations of the arc current are reduced and so is the rms value of the source current .



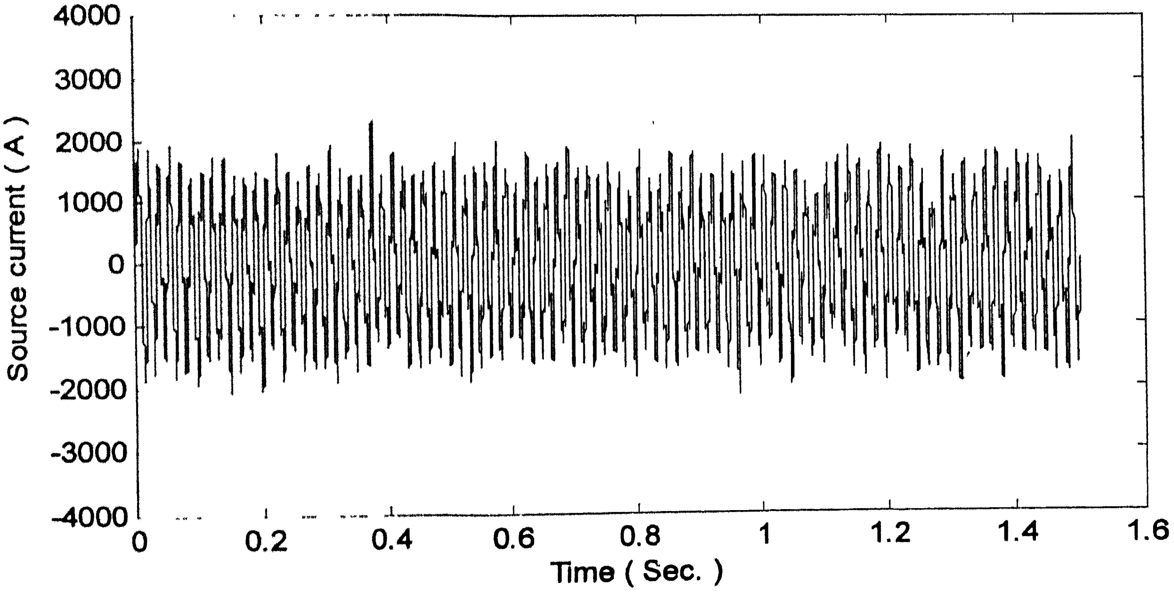


Figure 6.20 : Load and source current

The harmonic content in the current drawn from the source is reduced considerably as shown in the figures 6.21a and 6.21b.

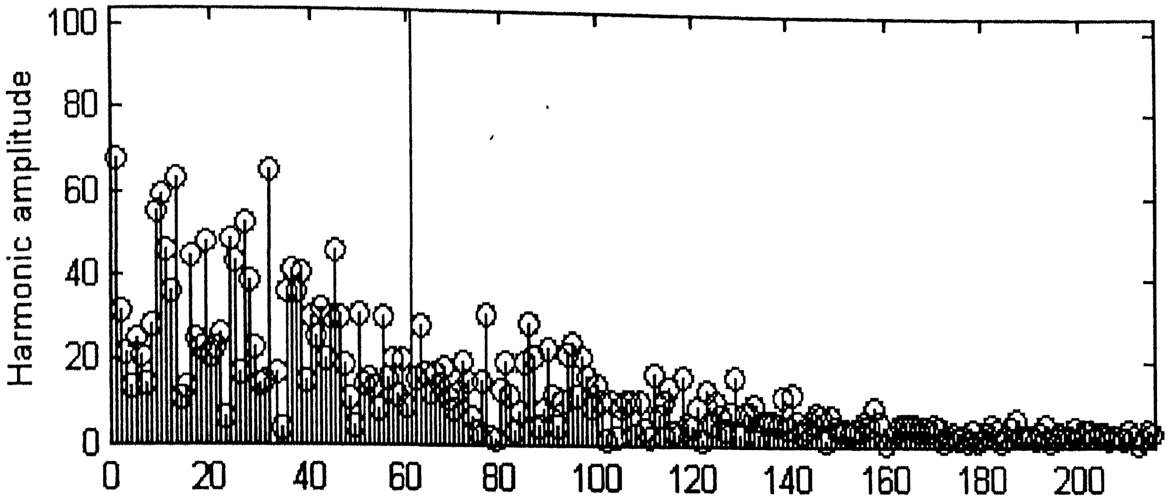


Figure 6.21a : Load current harmonic spectrum

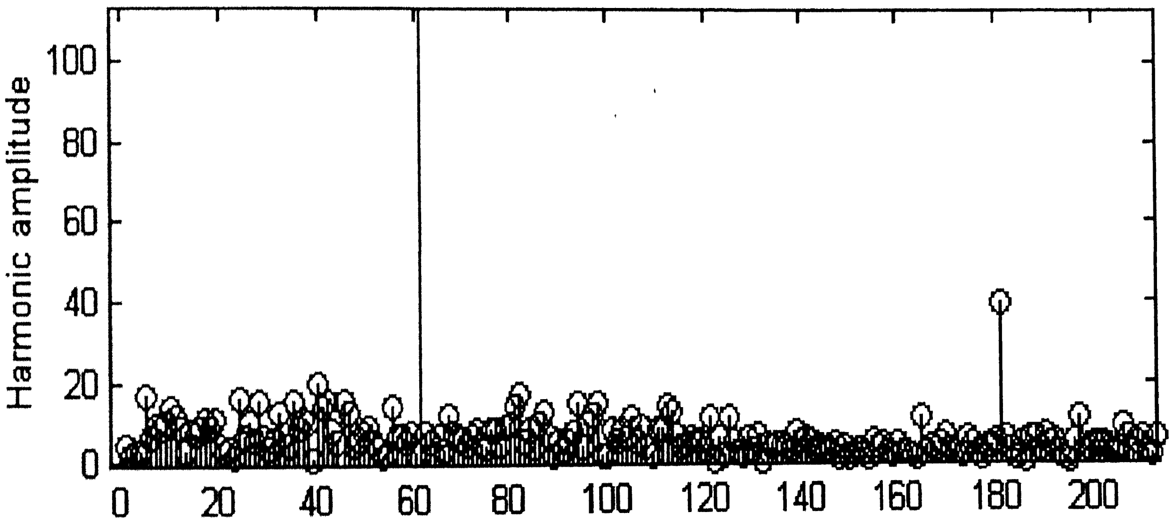


Figure 6.21b : Source current harmonic spectrum

The figures shown above indicate the effectiveness of the method of compensation using a voltage source inverter and the algorithm proposed by Watanabae for the instantaneous compensation of the entire reactive and the harmonic real power.

The figure 6.22 below also highlight the improvement in the power factor of the arc furnace as seen by the source,

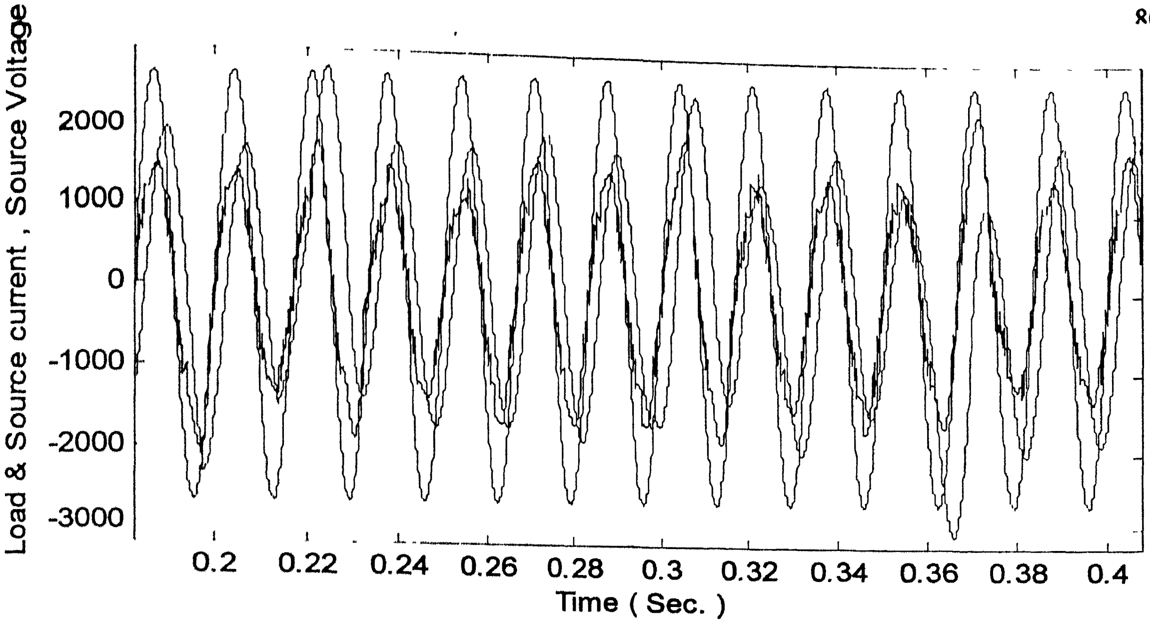


Figure 6.22 : Load and source current along with source voltage

6.5.4 Compensator current and reference current

The figures 6.23 shows the required i.e the reference current along with the actual compensator current. It can be seen that the compensator current tracks the reference current but with a small time lag which is because of the time constant of the inverter. This value cannot be made very small or else we will have sharp spikes in the current which will be reflected in the voltage waveform also.

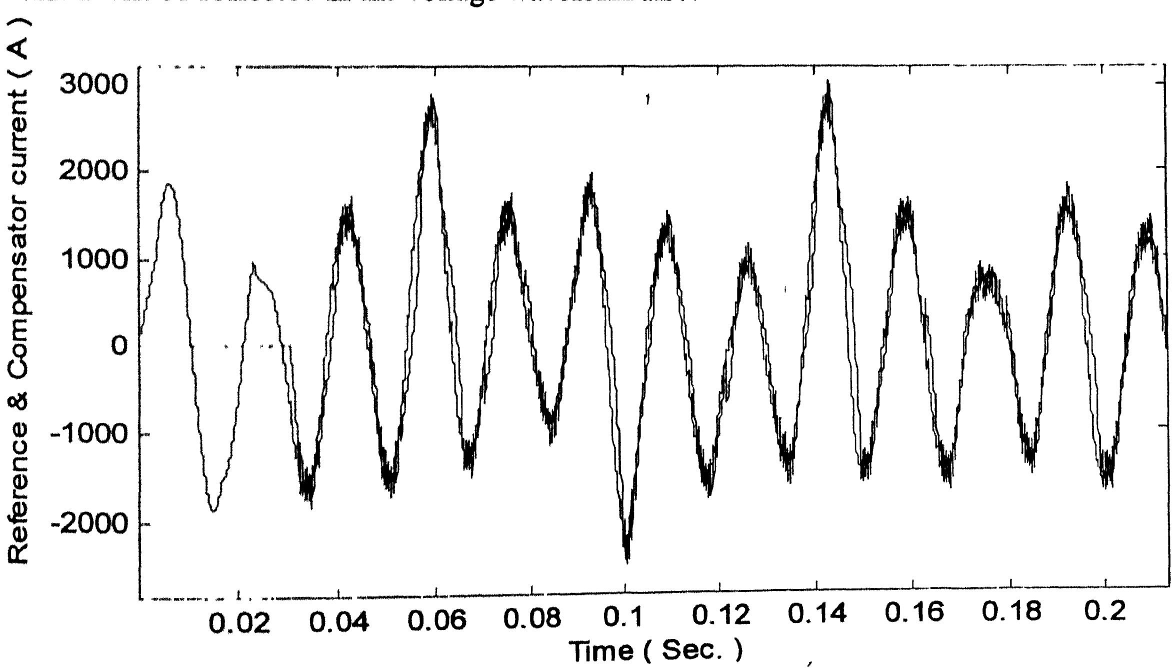


Figure 6.23 : Reference and the compensator current

6.5.5 Capacitor voltage

The figure 6.24 shows the waveform of the capacitor voltage of the inverter. It can be seen that voltage is in fact maintained through proper modification of the required reference current taking into account the losses of the inverter configuration.

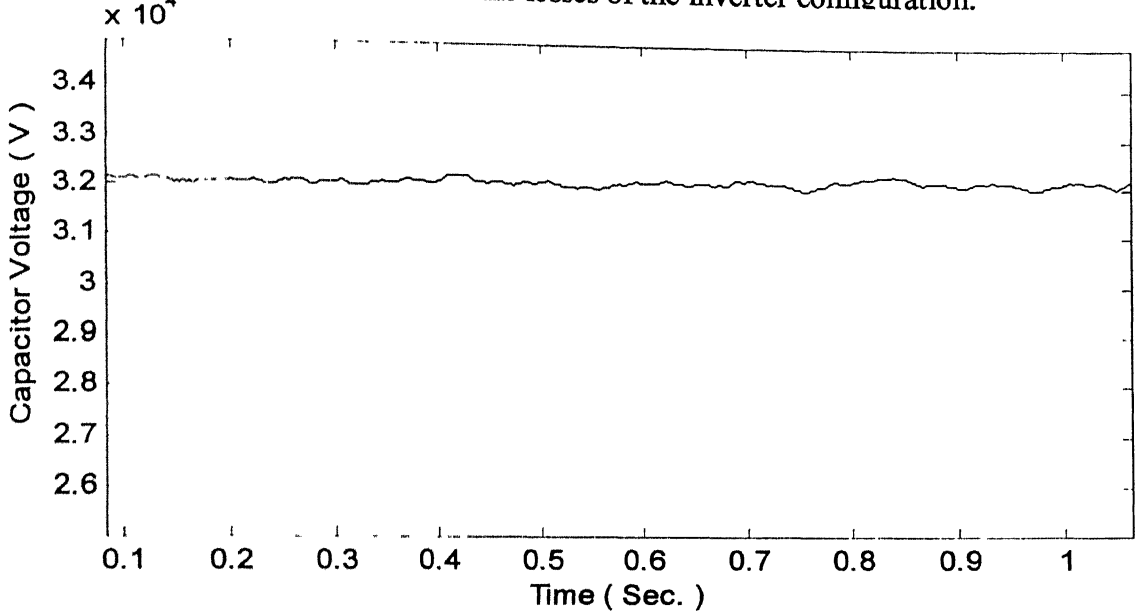


Figure 6.24 : Capacitor voltage of the inverter

6.5.6 Real and reactive power

The real and reactive being consumed by the load and that being supplied by the source is shown in the figures 6.25 and 6.26 given below,

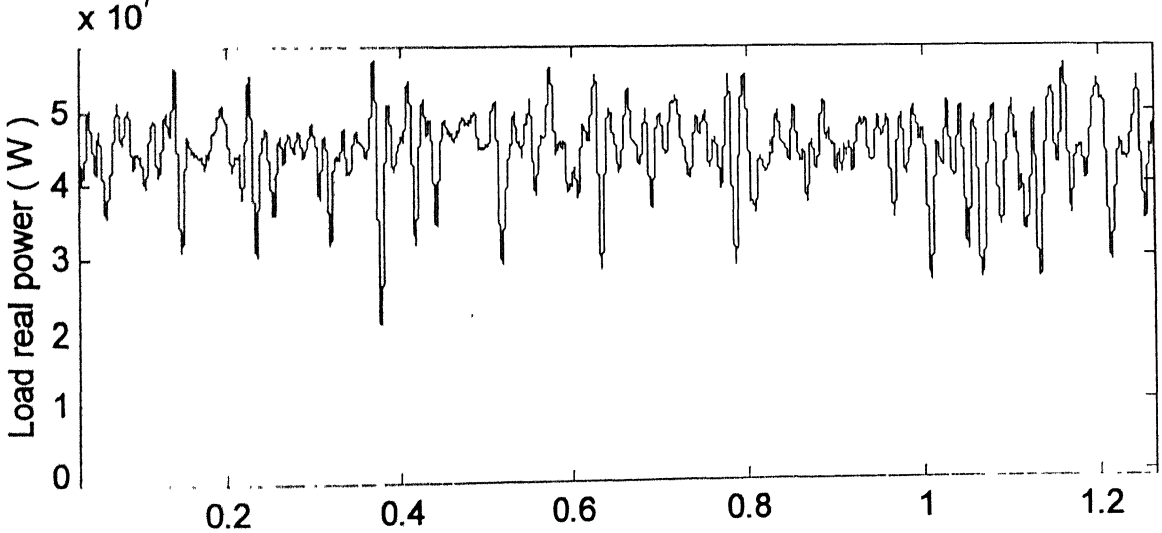


Figure 6.25a : Load real power

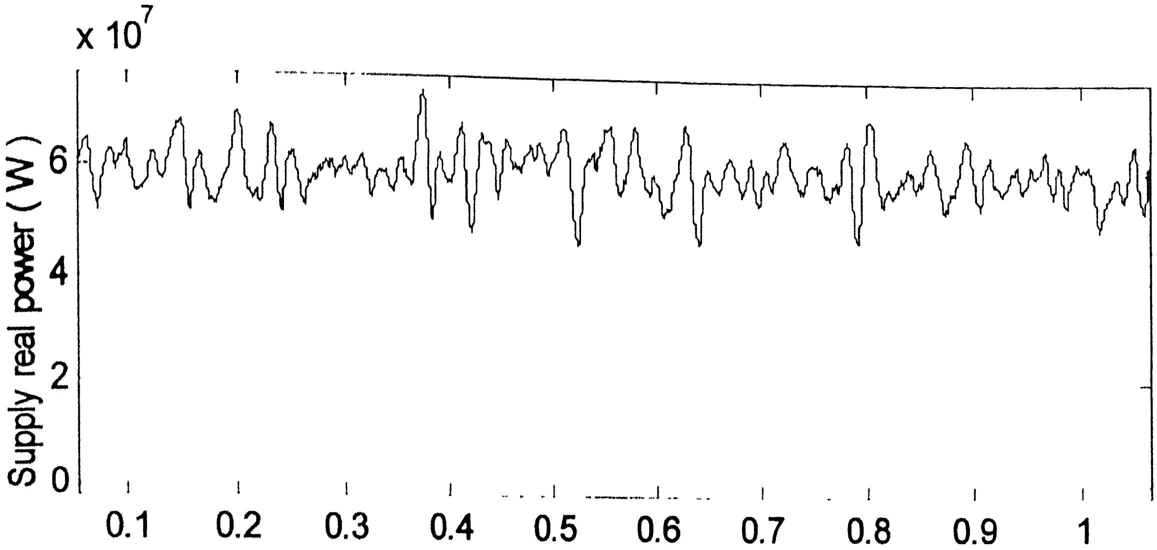


Figure 6.25b : Source real power

It is clear from the above figures that the real power being supplied by the source has relatively lower fluctuations. The figures below show the reactive power being consumed by the load and that being supplied by the source,

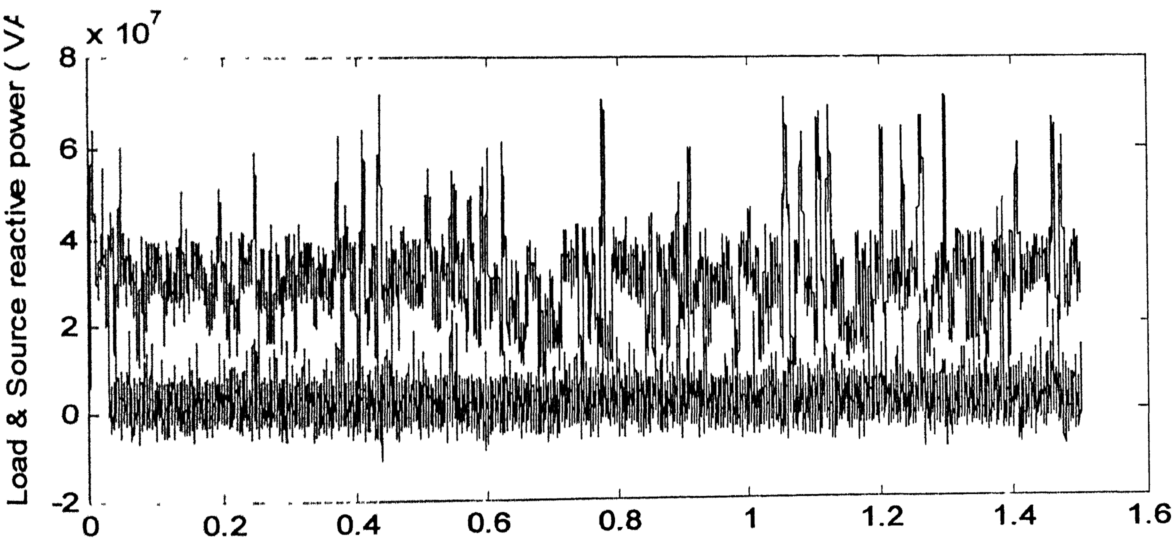


Figure 6.26 : Load and source reactive power

The above figure shows the reduction in the reactive power that the source has to supply after the compensation of the reactive current in the load circuit. Thus it can be said that now the load is virtually a balanced resistive type of load to a great extent.

6.5.7 Voltage and flicker at the critical bus

The voltage profile at the critical bus is improved considerably after compensation . The figure 6.27 shows the critical bus voltage along with the supply voltage. It can be seen that the r.m.s. value of the bus voltage after compensation is almost equal to the supply voltage but some voltage spikes are introduced in the voltage waveform because of the rapid changes in the inverter current due to switching in the inverter circuit.

The figures also indicate the reduction in the harmonic content of the voltage at the critical bus.

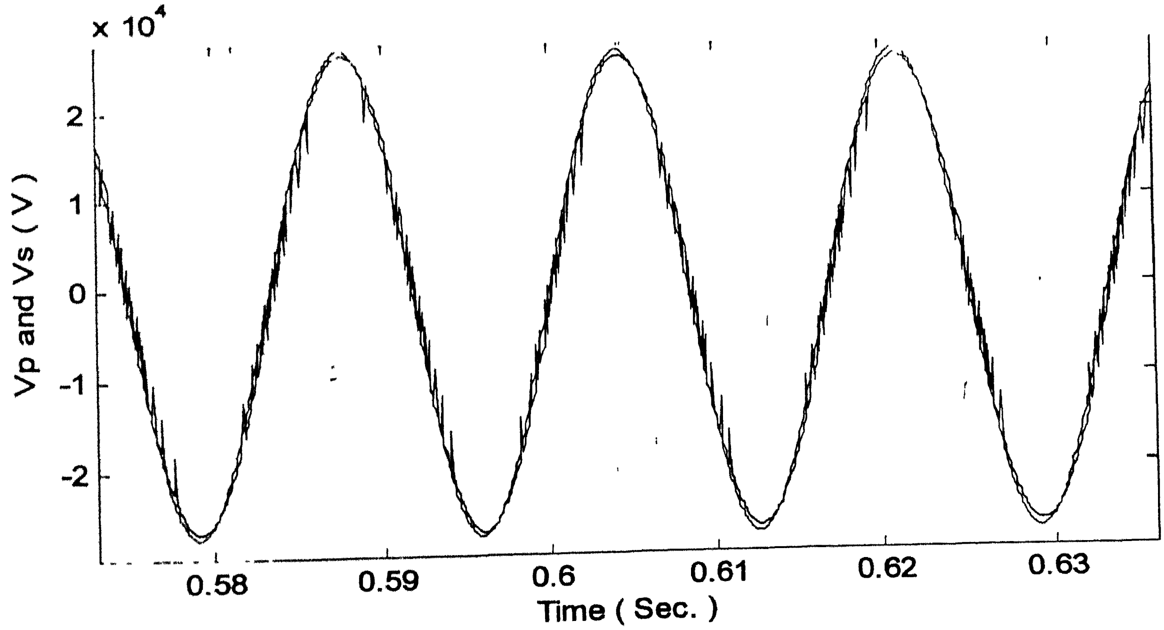


Figure 6.27 : Source and the critical bus voltage

The figure 6.28 shows the rms value of the bus voltage. By comparing this figure with the corresponding figure in chapter 3 we can see the improvement in the average r.m.s. value after compensation.

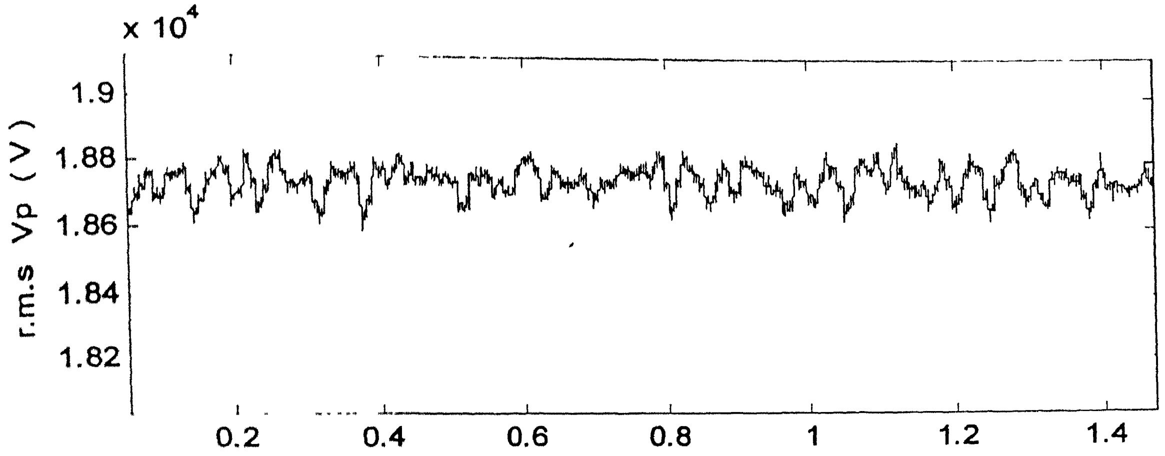


Figure 6.28 : r.m.s. voltage at the critical bus

The figure 6.29 given below shows the harmonic spectrum of the voltage at the critical bus. It can be seen that all the low frequency harmonics are suppressed significantly thus improving the quality of power at the critical bus.

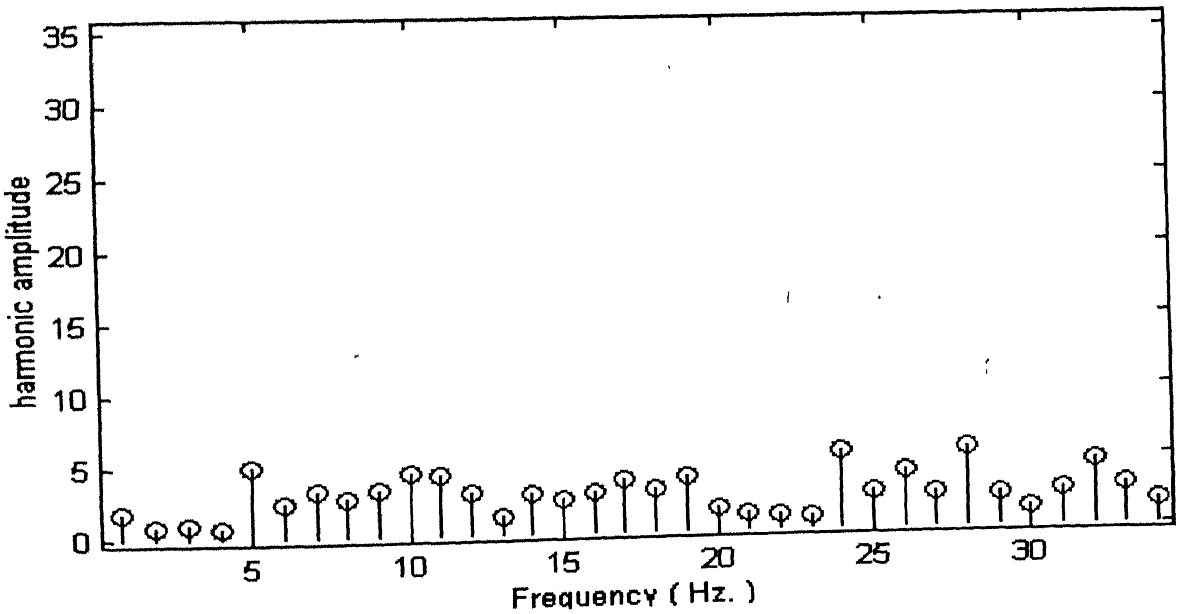


Figure 6.29 : Harmonic spectrum of the critical bus voltage

The reduction in the harmonic content of the bus voltage suppresses the problem of flicker as shown below.

The level of flicker at the critical bus , after compensation , is found to be ,

$$\Delta V_{10} = 12 \cdot 8$$

this is an improvement of around 78% and is quite close to that obtained for the case of ideal current source and highlights the accuracy of the theory for the purpose of instantaneous compensation of arc furnace systems.

6.6Conclusions

It has been shown in this chapter that we can achieve excellent compensation by using the theory mentioned in chapter 5 for instantaneous compensation of different components of power consumed by the load.

Thus this chapter highlights the importance of instantaneous current compensation scheme for effective control of the problem of flicker. It can be seen that the flicker level has been reduced by as much as 83% in case of compensation with an ideal current source and by 78% in case of compensation with a 2level 3phase inverter.

It can also be seen that we have some spikes in the voltage waveform at the critical bus which are due to different rates of change of current through the inverter during different time intervals. These spikes can be reduced by using multilevel inverters and also by using different switching schemes .

Chapter 7

CONCLUSIONS

In this thesis an arc model has been constructed so as to simulate an actual arc for randomness, harmonic content and power utilization. Arc furnace installation has been simulated and its behavior highlighted without any compensating aids thus bringing out the necessity of compensation. Flicker has been defined and evaluated at the critical bus.It has been shown that the arc current has a large harmonic content and that the arc furnace draws randomly fluctuating real and reactive powers from the supply, leading to voltage fluctuations at the critical bus .A high flicker level brings out the importance of flicker management.

Next we simulated an arc furnace system with a shunt connected S.V.C. It has been shown that although we are able to bring down the average reactive power required by the furnace but still a S.V.C as such is incapable of reducing the harmonics to any considerable extent. It has also been shown that a S.V.C has a limited affect as far as

flicker is concerned basically because it compensates for the fundamental reactive current only. Thus, it has been brought out that an arc furnace does require a fast and rapidly variable compensation so as to put a check on the problem of flicker.

Knowing the need of fast compensation, various instantaneous compensation schemes were considered and a new scheme of compensation based on the theory proposed by Lai [10] and that proposed by Watanabae [13] has been considered.

Next, the same arc furnace system has been simulated, but with the new compensation scheme using an ideal current source. It has been shown that the harmonic content in the supply current and voltage at the critical bus were reduced to a great extent. The reactive power required from the supply also went down to near zero and also there was a reduction in the fluctuations of real power. Flicker was reduced substantially thus showing a excellent improvement in the behavior of the system. Then we realized the ideal current source with a 2level 3phase inverter using current feedback. It has been shown that the system still behaves considerably better than those that have been compensated using S.V.C's.

Thus it was brought out that instantaneous current compensation method described in this study has excellent performance as compared to conventional methods. Although the 2level 3phase inverter introduces harmonics at switching frequency but still it reduces flicker to substantially lower levels.

Scope for further work

The following the areas which still require some attention,

- The inverter used for compensation needs to be upgraded in the sense that the switching frequency should be made more or less constant so that we have lesser spikes in the current waveform which are reflected in the voltage at the critical bus.

- Practical implementation of the theory could be done so as to verify the theoretical results obtained in this study.

- Investigations should be done so as to see the affect of replacing the 2level inverter with higher level inverters.

- Modifications in the reference current generator scheme should be investigated so as to sense the fluctuations in the real power drawn by the arc furnace more accurately.

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APPENDIX

A.1 Program for compensation of arc furnace with S.V.C.

```
clear all

global k      Td     t
global w      Vs     Va     Vb     Vc
global Rs     Ls1    Ls2    Ls     Rt     Lt
global R1     R2     R3     R4     R5     Ra     Rb     Rc
global Lf     Cf     L      Ilo    Ico    Ka     Kb     Kc
global ALFa   ALFb   ALFc   ja     jb     jc     ThetaA ThetaB ThetaC
global Aoa    Boa    Aob    Bob    Aoc    Boc
global A1a    B1a    A1b    B1b    A1c    B1c
global A2a    B2a    A2b    B2b    A2c    B2c
global Xa     Xb     Xc     Ql     Qs     Vp
global V1a    V2a    V1b    V2b    V1c    V2c

Td=1/36000;
w = 100*pi ;Vs=33000*sqrt(2/3) ;
Rs=0.254 ; Ls1=0.00006 ;
Rt=0.06  ; Ls2=0.00238   ;
Ls = Ls1 + Ls2 ; Lt = 0.03 ;
R1=3 ; R2=8 ; R3=10 ; R4=15 ; R5 = 20 ;
Cf = 0.0001 ; L = 0.05 ;Lf = 1/(9*w*w*Cf) ;
Ilo = Vs/(w*L) ; Ico =- Vs*w*Cf/(w*w*Lf*Cf-1) ;
Tc = 0.1 ; Tf = 0.5 ;

k    = 1 ;
t(1) = 0 ;
Va(k) = Vs*sin(w*t(k))          ;
Vb(k) = Vs*sin(w*t(k) - 2*pi/3) ;
Vc(k) = Vs*sin(w*t(k) + 2*pi/3) ;
Xa(:,1) = [ 0 ; 0 ; 0 ; 0 ] ;
Xb(:,1) = [ 0 ; 0 ; 0 ; 0 ] ;
Xc(:,1) = [ 0 ; 0 ; 0 ; 0 ] ;
Vp(:,1) = [ 0 ; 0 ; 0 ] ;
Ql(:,1) = [ 0 ; 0 ; 0 ] ;
Qs(:,1) = [ 0 ; 0 ; 0 ] ;
ja = 0 ; jb = 0 ; jc = 0 ;
Ka = 0 ; Kb = 0 ; Kc = 0 ;
Matrix ;
ThetaA = 4000 ; ThetaB = 4000 ; ThetaC = 4000 ;
Ca = 0 ; Cb = 0 ; Cc = 0 ;

while ( t(k) < Tc )

   k = k + 1 ;
   Matrix ;

   Xa(:,k) = uncomp( Aoa,Boa,Xa(:,(k-1)),Va(k-1) ) ; ja = ja + 1 ;
   Vp(1,k)  = uncompBusV( Xa(2,(k-1)),Ra,Va(k-1) )  ;

   Xb(:,k) = uncomp( Aob,Bob,Xb(:,(k-1)),Vb(k-1) ) ; jb = jb + 1 ;
   Vp(2,k)  = uncompBusV( Xb(2,(k-1)),Rb,Vb(k-1) )  ;

   Xc(:,k) = uncomp( Aoc,Boc,Xc(:,(k-1)),Vc(k-1) ) ; jc = jc + 1 ;
   Vp(1,k)  = uncompBusV( Xc(2,(k-1)),Rc,Vc(k-1) )  ;

   updateTVQ  ;
end

ThyA = 0 ; ThyB = 0 ; ThyC = 0 ;
while ( ( t(k) >= Tc )&( t(k) < (Tc + 2*pi/w) ) )
          k = k + 1 ;
          Matrix ;
      if     ( (peakvoltage( Vp(1,:) ))|(Ca == 1) )
```

```
            Ca       = 1 ;
            Xa(:,k) = cpcomp( A1a,B1a,Xa(:,(k-1)),Va(k-1) )     ; ja = ja + 1 ;
            Vp(1,k)  = compBusV( V1a,V2a,Ra,Xa(:,(k-1)),Va(k-1),ThyA ) ;
      elseif ( Ca == 0 )
            Xa(:,k) = uncomp( Aoa,Boa,Xa(:,(k-1)),Va(k-1) ) ;ja = ja + 1;
            Vp(1,k)  = uncompBusV( Xa(2,(k-1)),Ra,Va(k-1) )   ;
      else  error('unexpected situation') ;
      end
      if    ( (peakvoltage( Vp(2,:) ))|(Cb == 1) )
            Cb       = 1 ;
            Xb(:,k) = cpcomp( A1b,B1b,Xb(:,(k-1)),Vb(k-1) ) ; jb = jb + 1 ;
            Vp(2,k)  = compBusV( V1b,V2b,Rb,Xb(:,(k-1)),Vb(k-1),ThyB ) ;
      elseif ( Cb == 0 )
            Xb(:,k) = uncomp( Aob,Bob,Xb(:,(k-1)),Vb(k-1) ) ;jb = jb + 1;
            Vp(2,k)  = uncompBusV( Xb(2,(k-1)),Rb,Vb(k-1) )   ;
      else  error('unexpected situation') ;
      end
      if    ( (peakvoltage( Vp(3,:) ))|(Cc == 1 ) )
            Cc       = 1 ;
            Xc(:,k) = cpcomp( A1c,B1c,Xc(:,(k-1)),Vc(k-1) ) ;jc = jc + 1 ;
            Vp(3,k)  = compBusV( V1c,V2c,Rc,Xc(:,(k-1)),Vc(k-1),ThyC ) ;
      elseif ( Cc == 0 )
            Xc(:,k) = uncomp( Aoc,Boc,Xc(:,(k-1)),Vc(k-1) ) ;jc = jc + 1;
            Vp(3,k)  = uncompBusV( Xc(2,(k-1)),Rc,Vc(k-1) )   ;
      else  error('unexpected situation') ;
      end
   updateTVQ ;
end

ThyA = 0 ; ThyB = 0 ; ThyC = 0 ;
AbortA = 0 ; AbortB = 0 ; AbortC = 0 ;
while ( t(k) < Tf )
   k = k + 1 ;
   if     ( k < ThetaA )
                 if   ( zerocrossing( Vp(1,:) ) )
                      ThyA = 0 ;
                      AbortA = 1 ;
                 else ThyA = 0 ;
                 end
   elseif ( k == ThetaA )
                 if   ( AbortA == 0 )
                      ThyA = 1 ;
                 elseif ( AbortA == 1 )
                      ThyA = 0 ;
                 else error('check firing') ;
                 end
   elseif ( k  > ThetaA )
                 if   ( AbortA == 0 )
                    if (( zerocrossing( Xa(4,:) ) == 0 )&( ThyA == 1 ))
                      ThyA = 1 ;
                    elseif (( zerocrossing( Xa(4,:)) == 1 )|( Xa(4,(k-1)) == 0 ))
                      ThyA = 0 ;
                      Xa(4,(k-1)) = 0 ;
                    end
                 elseif ( AbortA == 1 )
                     ThyA = 0 ;
                 else error('check after firing instant of ThyA') ;
                 end
   else   error('unexpected logic') ;
   end
    if     ( k < ThetaB )
                 if   ( zerocrossing( Vp(2,:) ) )
                      ThyB = 0 ;
                      AbortB = 1 ;
                 else ThyB = 0 ;
                 end
   elseif ( k == ThetaB )
                 if   ( AbortB == 0 )
                      ThyB = 1 ;
                 elseif ( AbortB == 1 )
                      ThyB = 0 ;
```

```
              else error('check firing') ;
              end
elseif ( k   > ThetaB )
              if    ( AbortB == 0 )
                 if (( zerocrossing( Xb(4,:) ) == 0 )&( ThyB == 1 ))
                    ThyB = 1 ;
                 elseif (( zerocrossing( Xb(4,:)) == 1 )|( Xb(4,(k-1)) == 0 ))
                    ThyB = 0 ;
                    Xb(4,(k-1)) = 0 ;
                 end
              elseif ( AbortB == 1 )
                   ThyB = 0 ;
              else error('check after firing instant of ThyA') ;
              end
else    error('unexpected logic') ;
end
if      ( k < ThetaC )
              if    ( zerocrossing( Vp(3,:) ) )
                    ThyC = 0 ;
                    AbortC = 1 ;
              else  ThyC = 0 ;
              end
elseif ( k == ThetaC )
              if    ( AbortC == 0 )
                    ThyC = 1 ;
              elseif ( AbortC == 1 )
                    ThyC = 0 ;
              else error('check firing') ;
              end
elseif ( k   > ThetaC )
              if    ( AbortC == 0 )
                 if (( zerocrossing( Xc(4,:) ) == 0 )&( ThyC == 1 ))
                    ThyC = 1 ;
                 elseif (( zerocrossing( Xc(4,:)) == 1 )|( Xc(4,(k-1)) == 0 ))
                    ThyC = 0 ;
                    Xc(4,(k-1)) = 0 ;
                 end
              elseif ( AbortC == 1 )
                   ThyC = 0 ;
              else error('check after firing instant of ThyA') ;
              end
else    error('unexpected logic') ;
end

Matrix ;

Xa(:,k) = flcomp(A1a,B1a,A2a,B2a,Xa(:,(k-1)),Va(k-1),ThyA) ;ja = ja + 1 ;
Vp(1,k) = compBusV( V1a,V2a,Ra,Xa(:,(k-1)),Va(k-1),ThyA ) ;

Xb(:,k) = flcomp(A1b,B1b,A2b,B2b,Xb(:,(k-1)),Vb(k-1),ThyB) ;jb = jb + 1 ;
Vp(2,k) = compBusV( V1b,V2b,Rb,Xb(:,(k-1)),Vb(k-1),ThyB ) ;

Xc(:,k) = flcomp(A1c,B1c,A2c,B2c,Xc(:,(k-1)),Vc(k-1),ThyC) ;jc = jc + 1 ;
Vp(3,k) = compBusV( V1c,V2c,Rc,Xc(:,(k-1)),Vc(k-1),ThyC ) ;

updateTVQ       ;

if ( ( ThyA == 0 )&(peakvoltage( Vp(1,:) ) == 1) )
       Iqa    = updateIQ( Q1(1,:) ) ;
       ThetaA = updateALFA(Iqa) ;
       AbortA = 0 ;
end
if ( ( ThyB == 0 )&(peakvoltage( Vp(2,:) ) == 1) )

       Iqb    = updateIQ( Q1(2,:) ) ;
       ThetaB = updateALFA(Iqb) ;
       AbortB = 0 ;
end
if ( ( ThyC == 0 )&(peakvoltage( Vp(3,:) ) == 1) )
       Iqc    = updateIQ( Q1(3,:) ) ;
       ThetaC = updateALFA(Iqc) ;
```

```
            AbortC = 0 ;
    end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


function  Vp = updateBusV( Z , R , X , U )

global    Lt Rt

Vp = Z(1)*Lt*X(1)+(Lt*Z(2)+R+Rt)*X(2)+Lt*Z(3)*X(3)+Lt*Z(4)*X(4)+Lt*Z(5)*U ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function  RTN = updateALFA(Iq)

global k Ilo Ico

   alf(1) = pi/6 ; itemp(1)=0 ;Icount(1)=0 ;
   fire = pi/2 ;
   for ( p=2:180 )
                alf(p) = alf(p-1) + pi/540 ;
                itemp(p) = 2*Ilo*( pi/2 - alf(p) - (sin(2*alf(p)))/2 )/pi ;
                Icount(p) = Ico - itemp(p) ;
                      if ( Icount(2) > Iq )
                             fire = pi/6 ;
                      elseif (( Icount(p) > Iq )&( Icount(p-1) < Iq ))
                             fire = alf(p) ;
                      end
   end
   RTN  = round(fire*360/pi  + k) ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function  Vol = uncompBusV( I , R , U )

global    Rs Ls Rt Lt Ls1 Ls2

Vp  = (Ls*(R+Rt)-Rs*Lt)*I/(Ls+Lt) + Lt*U/(Lt+Ls) ;
Vol = Vp ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function  state = uncomp(F,G,X,U)

X = F*X + G*U ;
state = X ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function peak = peakvoltage(V)

global  k

peak = 0 ;
if ( ( abs(V(k-1)) < abs(V(k-2)) )&( abs(V(k-2)) > abs(V(k-3)) ) )
          if ( V(k-1) > 0 )
                 peak = 1 ;
          else if ( V(k-1) < 0 )

                 peak = -1 ;
               end
          end
     peak = abs(peak) ;
else
     peak = 0 ;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function Matrix

global ja Ka Ra jb Kb Rb jc Kc Rc
```

```
            if ( ja >= Ka )
                 ja = 0 ;
                 Temp = updateR ;
                 Ra = Temp(1) ;
                 Ka = Temp(2) ;
                 updatematA ;
            end
            if ( jb >= Kb )
                 jb = 0 ;
                 Temp = updateR ;
                 Rb = Temp(1) ; Kb = Temp(2) ;
                 updatematB ;
            end
            if ( jc >= Kc )
                 jc = 0 ;
                 Temp = updateR ;
                 Rc = Temp(1) ; Kc = Temp(2) ;
                 updatematC ;
            end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function  state = flcomp(F1,G1,F2,G2,X,U,Thy)

if      ( Thy == 0 )
            X = F1*X + G1*U ;
elseif  ( Thy == 1 )
            X = F2*X + G2*U ;
end
state = X ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function state = cpcomp(F,G,X,U)

X = F*X + G*U ;
state = X ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function  Vp = compBusV( Z1 , Z2 , R , X , U ,Thy )

global    Lt Rt

if      ( Thy == 0 )
Vp = Z1(1)*Lt*X(1)+(Lt*Z1(2)+R+Rt)*X(2)+Lt*Z1(3)*X(3)+Lt*Z1(4)*X(4)+Lt*Z1(5)*U ;
elseif  ( Thy == 1 )
Vp = Z2(1)*Lt*X(1)+(Lt*Z2(2)+R+Rt)*X(2)+Lt*Z2(3)*X(3)+Lt*Z2(4)*X(4)+Lt*Z2(5)*U ;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function  RTNI = updateIQ(Q)

global k Vs

 S = 0 ;
 if ( k > 360 )
   for m = 1:360
          S = S + Q(k+1-m) ;
   end
 end
   Qavg = S/360   ;
   RTNI    = Qavg/Vs ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function cross = zerocrossing( Y )

global k

        cross = 0 ;
        if ( ( Y(k-2) < 0 )&( Y(k-1) > 0 ) )
               cross = 1 ;
        elseif ( ( Y(k-2) > 0 )&( Y(k-1) < 0 ) )
               cross = -1 ;
```

```
        else   cross =  0 ;
        end
        cross = abs(cross) ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function updateTVQ

global   k t Td w Vs Va Vb Vc Xa Xb Xc Qla Qlb Qlc Qsa Qsb Qsc Vp Ql Qs
global   Vpa Vpb Vpc

t(k)  = t(k-1) + Td ;

Va(k) = Vs*sin(w*t(k))           ;
Vb(k) = Vs*sin(w*t(k) - 2*pi/3) ;
Vc(k) = Vs*sin(w*t(k) + 2*pi/3) ;

Ql(1,k) = -( ( Vp(2,k) * Xc(2,k) ) - ( Vp(3,k) * Xb(2,k) ) ) ;
Ql(2,k) = -( ( Vp(3,k) * Xa(2,k) ) - ( Vp(1,k) * Xc(2,k) ) ) ;
Ql(3,k) = -( ( Vp(1,k) * Xb(2,k) ) - ( Vp(2,k) * Xa(2,k) ) ) ;

Qs(1,k)=-((Vb(1,k)*(Xc(2,k)+Xc(3,k)+Xc(4,k))-(Vc(1,k)*(Xb(2,k)+Xb(3,k)+Xb(4,k))));
Qs(2,k)=-((Vc(1,k)*(Xa(2,k)+Xa(3,k)+Xa(4,k))-(Va(1,k)*(Xc(2,k)+Xc(3,k)+Xc(4,k))));
Qs(3,k)=-((Va(1,k)*(Xb(2,k)+Xb(3,k)+Xb(4,k))-(Vb(1,k)*(Xa(2,k)+Xa(3,k)+Xa(4,k))));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function  X = updateR

global  R1 R2 R3 R4 R5

m = rand*10 ;
              if ((m>=0)&(m<2))
                  R = R1 ; K = round(rand*100) ;
              elseif ((m>=2)&(m<4))
                  R = R2 ; K = round(rand*300) ;
              elseif ((m>=4)&(m<6))
                  R = R3 ; K = round(rand*200) ;
              elseif ((m>=6)&(m<8))
                  R = R4 ; K = round(rand*100) ;
              elseif ((m>=8)&(m<10))
                  R = R5 ; K = round(rand*50) ;
              end
X = [ R  K ] ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function updatematA

global Td
global Rs Ls Rt Lt Ra
global Lf Cf L
global Aoa Boa A1a B1a A2a B2a
global V1a V2a

R = Ra ;
DM = Ls*Lt*(1/Lf + 1/Ls + 1/Lt) ;
DN = Ls*Lt*(1/Lf + 1/Ls + 1/Lt + 1/L) ;
M1 =   Ls/(Lf*DM)                 ;      N1 = Ls/(Lf*DN)                              ;
M2 = -(Rs+(Ls/Lf + 1)*(R+Rt))/DM ;      N2 = -(Rs+(Ls/Lf + Ls/L + 1)*(R+Rt))/DN ;
M3 = -Rs/DM                       ;      N3 = -Rs/DN                                  ;
M4 =  0                           ;      N4 =  -Rs/DN                                 ;
M5 =  1/DM                        ;      N5 = 1/DN                                    ;

ao = [      0              0              0              0

            0        -(R+Rt+Rs)/(Lt+Ls)   0              0

            0              0              0              0

            0              0              0              0         ] ;

bo = [      0     ;     1/(Lt+Ls)    ;    0      ;       0         ] ;
```

```
a1 = [        0                  0                1/Cf              0
              M1                 M2               M3                0
       (Lt*M1 - 1)/Lf   (Lt*M2 + (R+Rt))/Lf    Lt*M3/Lf             0
              0                  0                0                 0        ] ;
b1 = [        0         ;        M5      ;     Lt*M5/Lf     ;       0        ] ;
a2 = [        0                  0                1/Cf              0
              N1                 N2               N3                N4
       (Lt*N1 - 1)/Lf   (Lt*N2 + (R+Rt))/Lf    Lt*N3/Lf          Lt*N4/Lf
          Lt*N1/L       (Lt*N2 + (R+Rt))/L     Lt*N3/L           Lt*N4/L     ] ;
b2 = [        0         ;        N5      ;     Lt*N5/Lf     ;    Lt*N5/L     ] ;

[Aoa,Boa] = c2d(ao,bo,Td) ;
[A1a,B1a] = c2d(a1,b1,Td) ;
[A2a,B2a] = c2d(a2,b2,Td) ;

V1a = [ M1 ; M2 ; M3 ; M4 ; M5 ] ;
V2a = [ N1 ; N2 ; N3 ; N4 ; N5 ] ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function updatematB

global Td
global Rs Ls Rt Lt Rb
global Lf Cf L
global Aob Bob A1b B1b A2b B2b
global V1b V2b

R = Rb ;
DM = Ls*Lt*(1/Lf + 1/Ls + 1/Lt) ;
DN = Ls*Lt*(1/Lf + 1/Ls + 1/Lt + 1/L) ;
M1 =   Ls/(Lf*DM)                  ;      N1 = Ls/(Lf*DN)                              ;
M2 = -(Rs+(Ls/Lf + 1)*(R+Rt))/DM ;      N2 = -(Rs+(Ls/Lf + Ls/L + 1)*(R+Rt))/DN ;
M3 = -Rs/DM                        ;      N3 = -Rs/DN                                  ;
M4 =   0                           ;      N4 =  -Rs/DN                                 ;
M5 =   1/DM                        ;      N5 = 1/DN                                    ;

ao = [        0                  0                0                 0
              0          -(R+Rt+Rs)/(Lt+Ls)       0                 0
              0                  0                0                 0
              0                  0                0                 0        ] ;
bo = [        0         ;    1/(Lt+Ls)   ;        0         ;       0        ] ;
a1 = [        0                  0                1/Cf              0
              M1                 M2               M3                0
       (Lt*M1 - 1)/Lf   (Lt*M2 + (R+Rt))/Lf    Lt*M3/Lf             0
              0                  0                0                 0        ] ;
b1 = [        0         ;        M5      ;     Lt*M5/Lf     ;       0        ] ;
a2 = [        0                  0                1/Cf              0
              N1                 N2               N3                N4
       (Lt*N1 - 1)/Lf   (Lt*N2 + (R+Rt))/Lf    Lt*N3/Lf          Lt*N4/Lf
```

```
        Lt*N1/L      (Lt*N2 + (R+Rt))/L     Lt*N3/L          Lt*N4/L   ] ;

b2 = [      0       ;        N5      ;      Lt*N5/Lf   ;     Lt*N5/L   ] ;

[Aob,Bob] = c2d(ao,bo,Td) ;
[A1b,B1b] = c2d(a1,b1,Td) ;
[A2b,B2b] = c2d(a2,b2,Td) ;

V1b = [ M1 ; M2 ; M3 ; M4 ; M5 ] ;
V2b = [ N1 ; N2 ; N3 ; N4 ; N5 ] ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function updatematC

global Td
global Rs Ls Rt Lt Rc
global Lf Cf L
global Aoc Boc A1c B1c A2c B2c
global V1c V2c

R = Rc ;
DM = Ls*Lt*(1/Lf + 1/Ls + 1/Lt) ;
DN = Ls*Lt*(1/Lf + 1/Ls + 1/Lt + 1/L) ;
M1 =   Ls/(Lf*DM)                    ;     N1 = Ls/(Lf*DN)                                 ;
M2 = -(Rs+(Ls/Lf + 1)*(R+Rt))/DM ;     N2 = -(Rs+(Ls/Lf + Ls/L + 1)*(R+Rt))/DN ;
M3 = -Rs/DM                          ;     N3 = -Rs/DN                                     ;
M4 =  0                              ;     N4 =  -Rs/DN                                    ;
M5 =  1/DM                           ;     N5 = 1/DN                                       ;

ao = [      0                 0                  0              0

            0          -(R+Rt+Rs)/(Lt+Ls)        0              0

            0                 0                  0              0

            0                 0                  0              0        ] ;

bo = [      0       ;     1/(Lt+Ls)      ;       0       ;      0        ] ;

a1 = [      0                 0                1/Cf             0

            M1                M2                 M3             0

      (Lt*M1 - 1)/Lf  (Lt*M2 + (R+Rt))/Lf    Lt*M3/Lf           0

            0                 0                  0              0        ] ;

b1 = [      0       ;        M5      ;      Lt*M5/Lf   ;        0        ] ;

a2 = [      0                 0                1/Cf             0

            N1                N2                 N3             N4

      (Lt*N1 - 1)/Lf  (Lt*N2 + (R+Rt))/Lf    Lt*N3/Lf        Lt*N4/Lf

        Lt*N1/L       (Lt*N2 + (R+Rt))/L     Lt*N3/L         Lt*N4/L   ] ;

b2 = [      0       ;        N5      ;      Lt*N5/Lf   ;     Lt*N5/L   ] ;

[Aoc,Boc] = c2d(ao,bo,Td) ;
[A1c,B1c] = c2d(a1,b1,Td) ;
[A2c,B2c] = c2d(a2,b2,Td) ;

V1c = [ M1 ; M2 ; M3 ; M4 ; M5 ] ;
V2c = [ N1 ; N2 ; N3 ; N4 ; N5 ] ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

A.2 Program for compensation of arc furnace with ideal current source

```
clear all

global R1 R2 R3 R4 R5 Ro
global Rs Ls Rt1 Lt1 Rt2 Lt2 Ra Rb Rc
global ja Ka jb Kb jc Kc
global F1a G1a F1b G1b F1c G1c
global A1a A2a B1a B2a A1b B1b A2b B2b A1c B1c A2c B2c
global Xa Xb Xc
global Il Fc Iq h pl Th Pl
global k t Td Tc w Vs Vo Ua Ub Uc Vp slope

Tc = 0.3 ; Tf = 1.5 ; Td = 2/(360*60) ;
f = 60 ; w = 2*pi*f ; Vo = 33000*sqrt(2/3) ;
slope = 1000000 ; h = 10 ; Th = round(1/(2*Td*f)) ;
R1 = 3 ; R2 = 8 ; R3 = 10 ; R4 = 15 ; R5 = 20 ;
Rs = 0.254 ; Ls = 0.00005 ;
Rt1= 0.06  ; Lt1= 0.001   ;
Rt2= 0.001 ; Lt2= 0.03    ;

k =1 ; t(k) = 0 ;
Vs(1,k) = Vo*sin(w*t(k)) ;
Vs(2,k) = Vo*sin(w*t(k) - 2*pi/3) ;
Vs(3,k) = Vo*sin(w*t(k) + 2*pi/3) ;
Xa(:,k) = [ 0 ; 0 ] ;
Xb(:,k) = [ 0 ; 0 ] ;
Xc(:,k) = [ 0 ; 0 ] ;
Il(:,k) = [ 0 ; 0 ; 0 ] ;
Is(:,k) = [ 0 ; 0 ; 0 ] ;
Iq(:,k) = [ 0 ; 0 ; 0 ] ;
pl(1) = 0 ; Pl(1) = 0 ;ps(1) = 0 ;
Fc(:,k) = [ 0 ; 0 ; 0 ] ;
Ql(:,k) = [ 0 ; 0 ; 0 ] ;
Qs(:,k) = [ 0 ; 0 ; 0 ] ;
ja = 0 ; jb = 0 ; jc = 0 ;
Ka = 0 ; Kb = 0 ; Kc = 0 ;
Ra = 0 ; Rb = 0 ; Rc = 0 ;
Ua(:,k) = [ Vs(1,k) ; Fc(1,k) ] ;
Ub(:,k) = [ Vs(2,k) ; Fc(2,k) ] ;
Uc(:,k) = [ Vs(3,k) ; Fc(3,k) ] ;

while ( t(k) < Tf )

k = k + 1 ;
t(k) = t(k-1) + Td ;
solve_phaseA ;
solve_phaseB ;
solve_phaseC ;
Il(1,k) = Xa(1,k) + Xa(2,k) ;
Il(2,k) = Xb(1,k) + Xb(2,k) ;
Il(3,k) = Xc(1,k) + Xc(2,k) ;
Is(1,k) = Xa(1,k) ;
Is(2,k) = Xb(1,k) ;
Is(3,k) = Xc(1,k) ;
Vp(1,k) = A1a*Xa(1,(k-1)) + A2a*Xa(2,(k-1)) + B1a*Vs(1,(k-1)) + B2a*Fc(1,(k-1)) ;
Vp(2,k) = A1b*Xb(1,(k-1)) + A2b*Xb(2,(k-1)) + B1b*Vs(2,(k-1)) + B2b*Fc(2,(k-1)) ;
Vp(3,k) = A1c*Xc(1,(k-1)) + A2c*Xc(2,(k-1)) + B1c*Vs(3,(k-1)) + B2c*Fc(3,(k-1)) ;
Vs(1,k) = Vo*sin(w*t(k)) ;
Vs(2,k) = Vo*sin(w*t(k) - 2*pi/3) ;
Vs(3,k) = Vo*sin(w*t(k) + 2*pi/3) ;
Ql(:,k) = updateQ(  Vp(:,k) , Il(:,k) ) ;
Qs(:,k) = updateQ(  Vs(:,k) , Is(:,k) ) ;
Iq(:,k) = updateIq( Vp(:,k) , Il(:,k) ) ;
ps(k)   = Vs(1,k)*Is(1,k) + Vs(2,k)*Is(2,k) + Vs(3,k)*Is(3,k) ;

if ( t(k) >= 1/60 )
        S = 0 ;
        for j = 1:Th
```

```
            S = S + ps(k-j+1) ;
        end
        Ps(k) = S/Th ;
end
    if ( t(k) > Tc )
                if ( Xa(2,k) <= ( Iq(1,k) - h ) )
                    Fc(1,k) =  slope ;
                elseif ( Xa(2,k) >= ( Iq(1,k) + h ) )
                    Fc(1,k) = -slope ;
                else Fc(1,k) = Fc(1,(k-1)) ;
                end
                if ( Xb(2,k) <= ( Iq(2,k) + h )- )
                    Fc(2,k) = slope ;
                elseif ( Xb(2,k) >= ( Iq(2,k) + h ) )
                    Fc(2,k) = -slope ;
                else Fc(2,k) = Fc(2,(k-1)) ;
                end
                if ( Xc(2,k) <= ( Iq(3,k) + h ) )
                    Fc(3,k) = slope ;
                elseif ( Xc(2,k) >= ( Iq(3,k) + h ) )
                    Fc(3,k) = -slope ;
                else Fc(3,k) = Fc(3,(k-1)) ;
                end
    else Fc(:,k) = [ 0 ; 0 ; 0 ] ;
    end
Ua(:,k) = [ Vs(1,k) ; Fc(1,k) ] ;
Ub(:,k) = [ Vs(2,k) ; Fc(2,k) ] ;
Uc(:,k) = [ Vs(3,k) ; Fc(3,k) ] ;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function  solve_phaseC

global k Td R1 R2 R3 R4 Ro
global Rs Ls Rt1 Lt1 Rt2 Lt2  Rc
global jc Kc
global F1c G1c
global Xc Uc
global A1c B1c A2c B2c

if ( jc >= Kc )

   jc = 0 ;Temp = updateR ; Rc = Temp(1) ; Kc = Temp(2) ;

   A1c = -(Rs + Rt1) + (Ls + Lt1)*(Rs + Rt1 + Rt2 + Rc)/(Ls + Lt1 + Lt2) ;
   A2c =  (Ls + Lt1)*(Rt2 + Rc)/(Ls + Lt1 + Lt2) ;
   B1c = -(Ls + Lt1)/(Ls + Lt1 + Lt2) + 1 ;
   B2c =  (Ls + Lt1)*Lt2/(Ls + Lt1 + Lt2) ;

   A11 = -(Rs + Rt1 + Rt2 + Rc)/(Ls + Lt1 + Lt2) ;
   A12 = -(Rt2 + Rc)/(Ls + Lt1 + Lt2) ;
   A21 = 0 ;
   A22 = 0 ;
   B11 = 1/(Ls + Lt1 + Lt2) ;
   B12 = -Lt2/(Ls + Lt1 + Lt2) ;
   B21 = 0 ;
   B22 = 1 ;

   Ac = [ A11  A12
          A21  A22 ] ;

   Bc = [ B11  B12
          B21  B22 ] ;

   [F1c G1c] = c2d(Ac,Bc,Td) ;

 end
Xc(:,k) = F1c*Xc(:,(k-1)) + G1c*Uc(:,(k-1)) ;
jc = jc + 1 ;
```

```
   Ba = [ B11  B12
          B21  B22 ] ;

   [Fla Gla] = c2d(Aa , Ba , Td) ;

end
Xa(:,k) = Fla*Xa(:,(k-1)) + Gla*Ua(:,(k-1)) ;
ja = ja + 1 ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function  X = updateR

global R1 R2 R3 R4 R5 Ro

m = rand*10 ;
              if ((m>=0)&(m<2))
                  R = R1 ;
              elseif ((m>=2)&(m<4))
                  R = R2 ;
              elseif ((m>=4)&(m<6))
                  R = R3 ;
              elseif ((m>=6)&(m<8))
                  R = R4 ;
              elseif ((m>=8)&(m<10))
                  R = R5 ;
              end

              if ( R == R1 )
                  K = round(rand*100) ;
              elseif ( R == R2 )
                  K = round(rand*300) ;
              elseif ( R == R3 )
                  K = round(rand*200) ;
              elseif ( R == R4 )
                  K = round(rand*100) ;
              elseif ( R == R5 )
                  K = round(rand*50) ;
              end
              X = [ R  K ] ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function Q = updateQ( V , I )

q1 = V(2)*I(3) - V(3)*I(2) ;
q2 = V(3)*I(1) - V(1)*I(3) ;
q3 = V(1)*I(2) - V(2)*I(1) ;

Q = [ -q1 ; -q2 ; -q3 ] ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function P = updateP( V , I )

P = V(1)*I(1) + V(2)*I(2) + V(3)*I(3) ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function  Current = updateIq( V , I )

global  t k pl Th Pl

       NormV = V(1)*V(1) + V(2)*V(2) + V(3)*V(3) ;
       pl(k) = V(1)*I(1) + V(2)*I(2) + V(3)*I(3) ;
       if ( t(k) >= 1/60 )
          S = 0 ;
          for j = 1:Th
             S = S + pl(k-j+1) ;
          end
          Pl(k) = S/Th ;
       elseif ( t(k) < 1/60 )
          Pl(k) = 0 ;
       end
       X1 = I(1) - Pl(k)*V(1)/NormV ;
```

```
      X2 = I(2) - Pl(k)*V(2)/NormV ;
      X3 = I(3) - Pl(k)*V(3)/NormV ;
      Current = [ X1 ; X2 ; X3 ]   ;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

A.3 Program for compensation of arc furnace with a current source realized through a 3phase 2level inverter

```
clear all

global R1 R2 R3 R4 R5 Ro Rf Lf
global Rs Ls Rt1 Lt1 Rt2 Lt2 Ra Rb Rc
global ja Ka jb Kb jc Kc
global F1a G1a F1b G1b F1c G1c
global A1a A2a B1a B2a A1b B1b A2b B2b A1c B1c A2c B2c
global Xa Xb Xc
global Il Fc Iq h pl Th Pl
global k t Td Tc w Vs Vo Ua Ub Uc Vp Vdc Vp Vc Cf Ploss

Tc = 0.03 ; Tf = 1.5 ; Td = 2/(360*60) ;
f = 60 ; w = 2*pi*f ; Vo = 33000*sqrt(2/3) ; Vdc = Vo*1.2 ; Kp = 10000.0 ;
h = 10 ; Th = round(1/(2*Td*f)) ; Rf = 0.01 ; Lf = 0.015 ; Cf = 0.01 ;
R1 = 3 ; R2 = 8 ; R3 = 10 ; R4 = 15 ; R5 = 20 ;
Rs = 0.254 ; Ls = 0.00005 ;
Rt1= 0.06  ; Lt1= 0.001   ;
Rt2= 0.001 ; Lt2= 0.03    ;

k =1 ; t(k) = 0 ; Vc(1) = Vdc ;
Vs(1,k) = Vo*sin(w*t(k)) ;
Vs(2,k) = Vo*sin(w*t(k) - 2*pi/3) ;
Vs(3,k) = Vo*sin(w*t(k) + 2*pi/3) ;
Xa(:,k) = [ 0 ; 0 ] ;
Xb(:,k) = [ 0 ; 0 ] ;
Xc(:,k) = [ 0 ; 0 ] ;
Il(:,k) = [ 0 ; 0 ; 0 ] ;
Is(:,k) = [ 0 ; 0 ; 0 ] ;
Iq(:,k) = [ 0 ; 0 ; 0 ] ;
pl(1) = 0 ; Pl(1) = 0 ;ps(1) = 0 ;
Fc(:,k) = [ 0 ; 0 ; 0 ] ;
Ql(:,k) = [ 0 ; 0 ; 0 ] ;
Qs(:,k) = [ 0 ; 0 ; 0 ] ;
ja = 0 ; jb = 0 ; jc = 0 ;
Ka = 0 ; Kb = 0 ; Kc = 0 ;
Ra = 0 ; Rb = 0 ; Rc = 0 ;
Ua(:,k) = [ Vs(1,k) ; Fc(1,k) ] ;
Ub(:,k) = [ Vs(2,k) ; Fc(2,k) ] ;
Uc(:,k) = [ Vs(3,k) ; Fc(3,k) ] ; Coun = 0 ;

while ( t(k) < Tf )

k = k + 1 ;
t(k) = t(k-1) + Td ;

solve_phaseA ;
solve_phaseB ;
solve_phaseC ;

Il(1,k) = Xa(1,k) + Xa(2,k) ;
Il(2,k) = Xb(1,k) + Xb(2,k) ;
Il(3,k) = Xc(1,k) + Xc(2,k) ;
Is(1,k) = Xa(1,k) ;
Is(2,k) = Xb(1,k) ;
Is(3,k) = Xc(1,k) ;
```

```
Vp(1,k) = A1a*Xa(1,(k-1)) + A2a*Xa(2,(k-1)) + B1a*Vs(1,(k-1)) + B2a*Fc(1,(k-1)) ;
Vp(2,k) = A1b*Xb(1,(k-1)) + A2b*Xb(2,(k-1)) + B1b*Vs(2,(k-1)) + B2b*Fc(2,(k-1)) ;
Vp(3,k) = A1c*Xc(1,(k-1)) + A2c*Xc(2,(k-1)) + B1c*Vs(3,(k-1)) + B2c*Fc(3,(k-1)) ;
Vs(1,k) = Vo*sin(w*t(k)) ;
Vs(2,k) = Vo*sin(w*t(k) - 2*pi/3) ;
Vs(3,k) = Vo*sin(w*t(k) + 2*pi/3) ;

updatecapV ;
Ploss = Kp*(Vdc - Vc(k))/3  ;
Coun = Coun + 1 ;
Ql(:,k) = updateQ(  Vp(:,k) , Il(:,k) ) ;
Qs(:,k) = updateQ(  Vs(:,k) , Is(:,k) ) ;
Iq(:,k) = updateIq( Vp(:,k) , Il(:,k) ) ;
ps(k)   = Vs(1,k)*Is(1,k) + Vs(2,k)*Is(2,k) + Vs(3,k)*Is(3,k) ;

if ( t(k) >= 1/60 )
        S = 0 ;
        for j = 1:Th

           S = S + ps(k-j+1) ;
        end
        Ps(k) = S/Th ;
end
    if ( t(k) > Tc )
                 if ( Xa(2,k) <= ( Iq(1,k) - h ) )
                     Fc(1,k) =  Vc(k) - Vp(1,k) ;
                 elseif ( Xa(2,k) >= ( Iq(1,k) + h ) )
                     Fc(1,k) = - Vc(k) - Vp(1,k) ;
                 else Fc(1,k) = Fc(1,(k-1)) ;
                 end
                 if ( Xb(2,k) <= ( Iq(2,k) - h ) )
                     Fc(2,k) = Vc(k) - Vp(2,k) ;
                 elseif ( Xb(2,k) >= ( Iq(2,k) + h ) )
                     Fc(2,k) = - Vc(k) - Vp(2,k) ;
                 else Fc(2,k) = Fc(2,(k-1)) ;
                 end
                 if ( Xc(2,k) <= ( Iq(3,k) - h ) )
                     Fc(3,k) = Vc(k) - Vp(3,k) ;
                 elseif ( Xc(2,k) >= ( Iq(3,k) + h ) )
                     Fc(3,k) = - Vc(k) - Vp(3,k) ;
                 else Fc(3,k) = Fc(3,(k-1)) ;
                 end
 else Fc(:,k) = [ 0 ; 0 ; 0 ] ;
 end
 Ua(:,k) = [ Vs(1,k) ; Fc(1,k) ] ;
 Ub(:,k) = [ Vs(2,k) ; Fc(2,k) ] ;
 Uc(:,k) = [ Vs(3,k) ; Fc(3,k) ] ;
 end

 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 function updatecapV ;

 global k Cf Vc Td Xa Xb Xc

 A = - ( Xa(2,k) + Xb(2,k) + Xc(2,k) )/Cf ;
 B = 0 ;

 [F G] = c2d( A , B , Td ) ;

 Vc(k) = Vc(k-1) + A*Td ;

 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

- All the other functions being called in A.3 are the same as those for A.2 .